PSD10: 10th International Conference on Position Sensitive Detectors

Sunday 07 September 2014 - Friday 12 September 2014

University of Surrey

Book of Abstracts

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(Invited) An overview of the STFC pixel detector programme

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The UK Science and Technology Facilities Council (STFC) deliver detector systems to large scale scientific facilities both in the UK and world-wide. It achieves this through a combination of central laboratory and university led projects and undertakes its own research and development programmes.
As part of this activity the STFC's central laboratories at Harwell, Daresbury and Edinburgh are engaged in the development, construction, delivery and ongoing support for pixel systems in scientific and commercial applications. This presentation will cover highlights from this programme including specific pixelated detector projects and underpinning technology developments for future programs for fields such as High Energy Physics applications, Nuclear Physics, Space Science, life sciences and other commercial applications.

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On-ground characterization of the Euclid's low noise CCD273 sensor for precise galaxy shape measurements

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Euclid is a medium class European Space Agency mission with a launch date scheduled for 2020. The survey is designed to study dark matter and energy of the Universe using two cosmological probes: weak gravitational lensing and baryonic acoustic oscillations. Weak lensing investigates the distortions caused to the galaxy shapes and relies on accurate shape measurements. The Euclid Visible Instrument (VIS) features a focal plane consisting of 36 CCD273 sensors manufactured by e2v technologies. The sensors are designed to provide a maximum charge transfer efficiency (CTE) to minimize geometrical distortions of the point sources. Each sensor undergoes a rigorous on-ground electro-optical testing at several stages of the mission to ensure that strict requirements are met before the lunch of the telescope. This paper will summarize the results of the commissioning of a single CCD273 device (before the integration into the focal plane) performed at the Mullard Space Science Laboratory (MSSL) with a special interest in the measurements of the point spread function (PSF). Additionally, the influence of the on-ground testing environment and a dedicated readout electronics on the obtained images will be taken into consideration.

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A coded aperture approach for particle measurements in space plasmas

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Current plasma analysis instruments in the near-Earth environment are limited in their capabilities of measuring angular distribution at a high resolution over a wide field of view, especially of higher energy electrons and ions.

A novel low-resource concept is proposed, using a coded aperture manufactured from high density material and a position sensitive detector capable of particle detection behind it. Deconvolution techniques applied to the resulting readout allow very accurate identification of directional particle fluxes. Such a setup could be used in an orbital situation where available on-board resources would not permit a larger or higher-power instrument, and where magnetic field lines are aligned in such a way that higher-energy charged particles may be strongly directional.
Simulations have been performed of such a setup, both in a laboratory and space situation, demonstrating the theoretical capabilities of such an instrument. This has then been compared to the results of an proof of concept setup using a specialised CCD and a radioactive beta source in a vacuum chamber. The potential possibilities for the instrument and further considered improvements in the detector choice and geometry is analysed and quantified.

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Experiment of the 30 cm-cube ETCC under the Intense Radiations with Proton Beam

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As the MeV gamma-ray telescope in the next generation, we are developing an electron-tracking Compton camera (ETCC). An ETCC consists of a gaseous time projection chamber and pixel scintillator arrays. Since the gaseous time projection chamber measures three dimensional tracks of Compton-recoil electrons, the ETCC can reconstruct gamma rays completely. Moreover, the ETCC has an efficient background rejection power based on Compton-kinematics test, particle identification using energy deposit rate, and high quality image by complete reconstruction. Proposing an all sky survey satellite, we are planning "Sub MeV gamma ray Imaging Loaded on balloon Experiment (SMILE)." In 2006, the first balloon (SMILE-I) was launched, and it was successful to detect the fluxes of diffuse cosmic and atmospheric gamma rays with a high efficient background rejection. At the next flight, we aim to a clear imaging of a bright celestial object such as Crab nebula (SMILE-II). For SMILE-II, we constructed a middle size ETCC using a 30 cm cube time projection chamber, and the performance test is ongoing. An observation at balloon altitude or satellite orbit is obstructed by many background. Especially, neutrons exist as many as gamma rays and are detected similar to Compton scattering. For checking the background rejection power, we carried out an experiment at Research Center for Nuclear Physics, Osaka university. We irradiated 140 MeV proton beam with the current of approximately 0.1 nA on a water target, and the SMILE-II ETCC was placed in the intense radiation field similar to the space, which is constructed with gamma rays, neutrons, protons, and so on. In this situation, we operated our 30 cm cube ETCC stably at 5 times higher counting rate than that expected at the balloon altitude, and it was successful to obtain a clear gamma-ray image of a checking source due to particle identification. We will report the performance of our detector and the efficient background rejection based on electron tracking. This results are also very important for radiation monitoring and particle therapy.

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Pre and Post Proton Irradiation Responsivity Mapping of the Swept Charge Device CCD236

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This work describes the responsitivty mapping of an e2v technolgies Swept Charge Device (SCD) CCD236 pre and post irradiation with a 10 MeV equivalent proton fluence of 5.0×108 protons.cm-2. The CCD236 is a large area (4.4 cm2) X-ray detector which will be used in India's Chandrayaan-2 Large Soft X-ray Spectrometer (CLASS) and China's Hard X-ray Modulation Telescope (HXMT). Due to the structure of the device, clocking is performed continuously resulting in a linear read out; the flat field illumination used to map the responsivity in conventional CCDs is not possible. An alternative masking technique has been used to expose pinpoint regions of the device to Mn-Ka and Mn-Kb X-rays, enabling a local responsivity map to be built up over the device. This novel approach also allows for an estimation of the charge transfer efficiency of the device to be made by allowing the creation of a CTI scatter plot similar to that typically observed in conventional CCDs.

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GaAs strip detector for high energy X-ray imaging

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A side-illuminated GaAs strip detector prototype for inspecting welds on copper canisters has been designed and is being manufactured. The detector has 512 channels and the strips are focused towards the radiation source, the distance between source and detector being 2200 mm. The X-ray beam is collimated to an area of 100mm x 0.2um on the edge of the detector by a collimator 150 mm in length, making alignment issues rather demanding. The copper canisters to be inspected will be used for final storage of spent nuclear fuel and therefore the imaging process needs to be fully automated and remote-controlled. The canisters are rotated in front of the detector at an angle of approximately 30 degrees. The thickness of copper that the X-rays need to pass through during weld inspection is up to 160 mm, which demands for a 9 MeV radiation source. The design goal is to be able to see volumetric defects as small as 1 x 1 x 1 mm 3. The 200 um strip pitch has been chosen to ensure this resolution and a strip length of 25 mm to offer enough stopping power for the high-energy X-rays in order to get a good signal. The strip detector is produced using high purity GaAs material grown by CVPE method (Chloride Vapour Phase Epitaxy) on n+ -type bulk GaAs wafers.
Readout is implemented with XCHIP readout ASICs and a high-speed DAQ module connected to a PC via Ethernet. The readout chips are protected from the incident X-rays by elevating them from the detector plane so that they are shielded by the collimator. This is achieved with a flex cable connection from the detector chip to the readout electronics. The final detector will be composed of two or three detectors similar to this prototype to facilitate stereoscopic radiography.

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Characterisation and performance comparison of two MYTHEN Cadmium-Telluride systems

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MYTHEN is a single photon counting hybrid strip X-ray detector that has found application in powder diffraction (XRPD) experiments at synchrotrons worldwide. Originally designed to operate with a silicon sensor, MYTHEN is ideally suited for detecting X-rays from 3-16 keV, however many XRPD beamlines have been designed for energies above 50keV. In order to adapt Mythen to meet these demands the absorption efficiency of the sensor must be substantially increased.
Cadmium-Telluride (CdTe) has demonstrated an absorption efficiency approximately 30 times that of silicon at 50 keV, and is therefore a very promising replacement candidate for silicon. Further, the large dynamic range of the pre-amplifier of MYTHEN and its double polarity has enabled two different configurations of CdTe sensors to be bonded and investigated. The first system has been used in an ohmic like electrons collecting processing, while the second system was used in a Schottky like holes collecting fashion. Both CdTe MYTHEN systems have undergone a series of characterisation experiments including stress test of bias and radiation induced polarizations. The performance comparison of both systems will be presented and discussed.

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Cadmium Telluride Spectroscopic X-Ray Imaging Detectors

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Over the last 10 years STFC have developed a range of small pixel spectroscopic imaging detectors based on Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CdZnTe) materials [1]. These detectors consistently produce excellent spectroscopic performance with greater than 98 % of pixels having a FWHM of 1 keV or better at 60 keV [2]. These detectors are now in use in a number of different application areas including materials science [3], homeland security [4] and medical imaging [5].
In this paper results are presented from the characterisation of 25 CdTe detectors with aluminium pixelated Schottky anodes. Each 1 mm thick detector consists of an array of 80 x 80 pixels on a 250 micron pitch that is flip-chip-bonded to the Hexitec spectroscopic ASIC [6]. Each of the 6,400 pixels of the detector produce a high resolution X-ray spectrum in the energy range 2-200 keV.
Using sealed radiation sources, the effects of bias voltage and operating temperature on the spectroscopic performance, stability and uniformity of these detectors will be characterised. Non-uniformities in the detector responses will also be investigated and related to the presence of crystal defects such as tellurium inclusions, dislocation walls and grain boundaries.
[1] S. D. M. Jacques, C. K. Egan, M. D. Wilson, M. C. Veale, P. Seller & R. J. Cernik. "A laboratory system for element specific hyperspectral imaging", Analyst, 138 (3), 755-759, 2013. http://dx.doi.org/10.1039/C2AN36157D
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[6] L. L. Jones, P. Seller, M. D. Wilson & A. Hardie. "HEXITEC ASIC – a pixelated readout chip for CZT detectors", Nuclear Instruments and Methods in Physics Research A, 604 (1-2), 34-37, 2009. http://dx.doi.org/10.1016/j.nima.2009.01.046

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The influence of operating conditions on Schottky CdTe Medipix3RX spectroscopic pixel detector performance

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Pixellated CdTe semiconductor detectors provide the stopping power that is needed for experiments performed at synchrotron radiation facilities at high photon energy (over 20 keV). Previous experiments conducted with CdTe Medipix detectors with Ohmic contacts showed defects that affect the image quality, as they cannot be corrected by flat field coefficient factors. Electron collection Schottky contact CdTe sensors show better imaging performance, however, they are affected by polarization. The focus of this project is to characterise and evaluate the performance of an electron collection Schottky contact CdTe sensor in terms of stability over time, degradation of performance with regards to temperature and flux since experiments at synchrotrons have high ionizing radiation flux, as well as, to understand the physics behind the defects.
An Acrorad electron collection Schottky contact CdTe sensor bump-bonded to a Medipix3RX ASICs developed by CERN and readout by the Merlin readout system developed by Diamond Light Source were tested for this study. The CdTe semiconductor sensor was segmented into a 128x128 pixel matrix with each pixel being 110µm pitch. The Medipix3 ASIC is a 256x256 pixel array with 55 µm pitch, every fourth pixel of the ASIC is bump-bonded to the sensor. Every pixel of the chip has two discriminators. Since the Medipix3 enable to cluster the discriminators of four pixels, each pixel of the sensor is equipped with eight discriminators. This allowed setting separate up to eight energy threshold windows for each of the 110µm pixels. This mode of operation is known as colour mode and gives spectral information in addition to spatial resolution. Three single type sensors of 128x128 pixel array and three quad type sensor with 256x256 pixel array (bump-bonded to 4 Medipix3 ASICs) were tested during this study.
The aim of the study was to test the behaviour the aforementioned setup in terms of uniformity, linearity, polarization effects and to create a map of optimum conditions such as temperature, flux and bias refresh time in order to find the best operational settings. The detectors were tested under various temperature (from 12°C to 24°C) and flux (2.5kcps per pixel to 30kcps per pixel) conditions in order to characterise the degradation of the pixel response over time. The degradation of the pixel response was studied by looking into each pixel's count rate variations and the changes in the total count rate inside the region of interest (ROI) over time. The tests showed that cooling the detector resulted in the reduction of the rate of degradation of the pixel response while higher flux resulted in increased degradation. Also, turning the applied bias voltage off for a short period of time and turning it back on depolarized the detector and, hence, recovered the performance of the pixels to the original state. Finding the optimum bias refresh time is crucial for optimal operation of the detector.
Despite the rate of the degradation being comparable for both of the single type detectors, two types of defects appeared after the detector was polarised. The defects were studied by investigating the response of each of the pixels in the ROI with an anomalous response. In the first case, the central pixel went dead and increasingly reduced the sensitivity of the nearby pixels

over time. In the second case, the central pixel went dead but the perpendicular pixels resulted in higher sensitivity.
This study showed that electron collection Schottky CdTe sensors can provide good imaging quality when operated under optimized operational conditions.

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Microbeam studies and simulation of a CZT Ring-Drift detector

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Ring-drift design has been applied for the first time to large (6mm) CZT detectors for hard x-ray spectroscopy. The detectors have also been modelled with Sentaurus TCAD, a powerful 3D tool. Our aim is to determine the electrode geometry and bias conditions that optimise energy resolution and sensitivity.\\
These devices are intended as a high-resolution room temperature photon detector for X-rays in the range 50-500keV. Drift designs operate as single-carrier detectors, sensitive only to electron transport throughout the active region. This overcomes the problem of poor hole transport in II-VI and other compound semiconductors. Our prototype cadmium zinc telluride (CZT) drift detector achieved resolution of 4.53 keV FWHM at an energy of 59.54 keV, limited predominantly by the electronic noise of our preamplifier system.
A previous study of CZT drift detectors [1] demonstrated complex variations in sensitivity with interaction position, biases and energy. The spatial response of our new CZT device was mapped by synchrotron microbeam scanning in order to investigate performance and charge transport variations over the surface area of the detector. Our data show that the detector performance is sensitive to optimal bias combinations and that the lateral 'drift' field exerts a crucial influence on active area, peak position and sensitivity.
Line scans were simulated in 3D with Sentaurus TCAD. A model of CZT material with realistic charge deposition and transport properties was first developed. The insight gained into fields and charge motion will be discussed. Energy shift and change in sensitivity with beam position matched experimental data, validating the model. Simulations will be repeated with varying geometry and bias conditions in search of optimum performance.
[1]A. Owens et al., "Hard X-ray response of a CdZnTe ring-drift detector"J. Appl.Phys., vol.102, no.5, pp 0545055

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The LAMBDA pixel detector with high-Z sensors

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Single-photon-counting pixel detectors provide high signal-to-noise ratios, fast readout, and sophisticated functionality, making them the technology of choice of many experiments at synchrotrons. LAMBDA (Large Area Medipix3-Based Detector Array) has been developed to improve on existing photon-counting systems. LAMBDA uses the Medipix3 readout chip, and

combines the small pixel size (55 μm) and flexibility of this chip with a large tileable module design of 1536 x 512 pixels (12 chips). The high-speed readout system currently runs at 1000 frames per second with no dead time between frames. Additionally, the system can be used in an energy-binning mode to provide additional information in experiments with polychromatic sources. A series of LAMBDA systems have been produced, commissioned and used in experiments at synchrotrons – for example, time-resolved experiments studying soft matter under shear forces.
To allow high-speed experiments with hard X-rays, the LAMBDA system has been combined with different high-Z sensor materials, in collaboration with other institutes and industry. Room-temperature systems using GaAs and CdTe systems have been assembled and tested at beamlines. These show acceptable image quality after flat-field correction. These first systems provide an area of 768 x 512 pixels, and larger systems using multiple tiled sensors are in development. The first Germanium hybrid pixel detectors have been also been produced. These have a layout of 256 x 256 pixels of 55μm, and work successfully. Due to the high quality of the sensor material, the germanium sensor provides a higher raw image uniformity. Larger germanium sensors are now in production.
To reduce the dead area in large LAMBDA systems, development has also started on a version of LAMBDA where the wire bonds are replaced with through-silicon vias, and the guard ring region is reduced by using an edgeless silicon sensor. The TSV processing will be done by Fraunhofer IZM. A radiation hard edgeless sensor layout is being designed using TCAD simulation.

Session 3: CERN@school joint session / 107

(Invited) Medipix and Timepix: introducing young people to nuclear and particle physics

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Hybrid silicon pixel detectors were developed to meet the requirements of vertex detection at the LHC. Three of the four large experiments are equipped with pixel vertex trackers and the fourth will upgrade to one soon. Hybrid pixel detectors were chosen because they provide hit information tagged to a single LHC bunch crossing with an extremely high signal to noise ratio. This information helps greatly to decode the complex events at the LHC. The Medipix and Timepix detectors use the same technology and approach to particle detection but their aim is more general purpose in nature. The Medipix chips (1, 2 and 3) provide photon or particle counting with varying degrees of energy resolution and binning options. The Timepix chip provides arrival time (ToA) or Time-over-Threshold (ToT) information on a frame-by-frame basis while the most recent Timepix3 chip provides both ToA and ToT information simultaneously in a data driven mode. This presentation will review the chip family highlighting the strengths and limitations of its various members. Particular emphasis is placed on how these devices and their associated compact readout systems have lead to applications in schools, in space and for other educational purposes.

Session 4: Pixel Detectors for High Energy Physics / 97

Achievements of the ATLAS Upgrade Planar Pixel Sensors R&D Project

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In the framework of the HL-LHC upgrade, the ATLAS experiment plans to introduce an all-silicon inner tracker with the HL-LHC upgrade to cope with the elevated occupancy.
To investigate the suitability of pixel sensors using the proven planar technology for the upgraded tracker, the ATLAS Planar Pixel Sensor R&D Project (PPS) was established comprising 19 institutes and more than 90 scientists. Main areas of research are

- performance assessment and improvement of planar pixel sensors at HL-LHC fluences
- the achievement of slim or active edges to provide low geometric inefficiencies without the need for shingling of modules
- establishment of reliable device simulations for severely radiation-damaged pixel detectors
- the exploration of possibilities for cost reduction to enable the instrumentation of large areas with pixel detectors

The presentation will give an overview of the R&D project and highlight accomplishments, among them

- beam test results with planar sensors up to innermost layer fluences ($>10^{16} n_{eq}/cm^2$)
- measurements obtained with irradiated thin edgeless n-in-p pixel assemblies
- recent studies of the SCP technique to obtain almost active edges by post-processing already existing sensors based on scribing, cleaving and edge passivation
- update on prototyping efforts for large areas: sensor design improvements, 6" wafer production experience, 8" wafer production possibilities, concepts for low-cost hybridisation

Together, these results will allow an assessment of the state-of-the-art with respect to radiation-hard position-sensitive tracking detectors suited for the instrumentation of large areas.

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The Pixel Detector of the ATLAS experiment for the Run2 at the Large Hadron Collider

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The Pixel Detector of the ATLAS experiment has shown excellent performance during the whole Run-1 of LHC. Taking advantage of the long showdown, the detector was extracted from the experiment and brought to surface, to equip it with new service quarter panels, to repair modules and to ease installation of the Insertable B-Layer (IBL). IBL is a fourth layer of pixel detectors, and will be installed in May 2014 between the existing Pixel Detector and a new smaller radius beam-pipe at a radius of 3.3 cm. To cope with the high radiation and pixel occupancy due to the proximity to the interaction point, a new read-out chip and two different silicon sensor technologies (planar and 3D) have been developed. Furthermore, the physics performance will be improved through the reduction of pixel size while, targeting for a low material budget, a new mechanical support using lightweight staves and a CO2 based cooling system have been adopted. IBL construction is now completed. An overview of the IBL project as well as the experience in its construction will be presented, focusing on adopted technologies, module and staves production, qualification of assembly procedure, integration of staves around the beam pipe and commissioning of the detector.

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The Upgrade of the LHCb Vertex Locator

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The upgrade of the LHCb experiment, planned for 2018, will transform the experiment to a trigger-less system reading out the full detector at 40 MHz event rate. All data reduction algorithms will be executed in a high-level software farm with access to the complete event

information. This will enable the detector to run at luminosities of 2 x 10^33 /cm^2/s and probe physics beyond the Standard Model in the heavy flavour sector with unprecedented precision.
The Vertex Locator (VELO) is surrounding the interaction region is used to reconstruct primary and secondary vertices and measure the flight distance of long-lived particles. The upgraded VELO must be capable of fast pattern recognition and track reconstruction while maintaining the exceptional resolution of the current detector. This is realised through a hybrid pixel detector using silicon sensors with 55x55 um^2 pitch, read out by the VeloPix ASIC which is being developed based on the TimePix/MediPix family. The hottest region will have pixel hit rates of 900 Mhits/s yielding a total data rate more than 3 Tbit/s for the upgraded VELO.
The detector modules are located in a separate vacuum, separated from the beam vacuum by a thin custom made foil. The foil will be manufactured through milling and possibly thinned further by chemical etching. The detector halves are retracted when the beams are injected and closed at stable beams, positioning the first sensitive pixel at 5.1 mm from the beams. The high data rates require development of low-mass, high-speed, flexible electrical serial links bringing the data out of the vacuum where electrical-to-optical conversion is performed.
The material budget will be minimised by the use of evaporative CO_2 coolant circulating in microchannels within 400 um thick silicon substrates. Microchannel cooling brings many advantages: very efficient heat transfer with almost no temperature gradients across the module, no CTE mismatch with silicon components, and low material contribution. This is a breakthrough technology being developed for LHCb.
The 40 MHz readout will also bring significant conceptual changes to the way in which the upgrade trigger is operated. Work is in progress to incorporate momentum and impact parameter information into the trigger at the earliest possible stage, using the fast pattern recognition capabilities of the upgraded detector. The current status of the VELO upgrade will be described together with a presentation of recent test results.

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CMS Pixel Phase I Upgrade

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The Phase I Upgrade of the CMS pixel detector includes changes in the readout electronics, the geometry of the detector and the cooling system. Each of this aspects will be summarized in this talk and the resulting improvements in physics performance discussed. Changes in the readout chip and the resulting performance will be highlighted. Ongoing work anticipating the production of the detector elements (pixel modules) including a pre-production of a limited amount of modules and the assessment of their performance and quality will be given in this talk.

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Development of CMOS Pixel Sensors for the Upgrade of the ALICE Inner Tracking System

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Development of CMOS Pixel Sensors for the Upgrade of the ALICE Inner Tracking System
V. Manzari (INFN Bari and CERN) on behalf of the ALICE Collaboration
The ALICE Collaboration is preparing a major upgrade of the current detector, planned for installation during the second long LHC shutdown in the years 2018-19, in order to enhance its low-momentum vertexing and tracking capability, and exploit the planned increase of the LHC luminosity with Pb beams. One of the cornerstone of the ALICE upgrade strategy is to replace the current Inner Tracking System in its entirety with a new, high resolution, low-material ITS

detector. The new ITS will consist of seven concentric layers equipped with Monolithic Active Pixel Sensors (MAPS) implemented using the 0.18 µm CMOS technology of TowerJazz. In this contribution, the main key features of the ITS upgrade will be illustrated with emphasis on the functionalities of the pixel chip. The ongoing developments on the readout architectures, which have been implemented in several fabricated prototypes, will be discussed. The operational features of these prototypes as well as the results of the characterization tests before and after irradiation will also be presented.

Session 5: Applications in Medicine and Proton Therapy / 134

(Invited) PRaVDA – An Integrated Proton Therapy Imaging System

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Proton therapy as an alternative to conventional radiotherapy is rapidly gaining momentum. Forty-eight treatment centres are in operation worldwide, with a further 38 planned or under construction. The first large-scale hospital-based facility opened in 1990. Some 100,000 patients have been treated using protons – a small fraction of the total numbers who have received radiotherapy as part of their curative treatment; but the prospects for much increased use of proton therapy for childhood cancers, tumours near critical organs and potentially the effective treatment of lung cancer.
Advantage of proton, and other charged hadron therapies, is the ability to deliver very high doses into small volumes, possibly deep inside a patient, with much reduced damage to surrounding healthy tissue. This is because protons produce more ionisation (and therefore cause more cellular damage) at one particular depth that is strongly dependant on the energy of the proton – the Bragg Peak. This prime advantage is also the major challenge.
PRaVDA is a consortium of six universities, four NHS Trusts, and the South African National Research Foundation (iThemba Laboratory for Accelerator-Based Sciences) that is developing a unique instrument for the real-time monitoring of proton dose and distribution as well as the creation of Proton CT imagery.
The instrument employs 12 custom strip detectors to track the individual protons entering and, under the imaging conditions, exiting the patient. The residual energy of the egressing protons is recorded using a range telescope consisting of 24 layers of wafer-scale radiation-hardened CMOS imagers operating at over 1,000 fps.
This presentation will discuss the design philosophy of the instrument, selected findings from extensive simulations and initial experiments on proton beams up to 200 MeV; as well as the theory and practice underlying the fully analytic reconstruction of Proton CT images. PRaVDA is supported by a Translational Grant awarded by the Wellcome Trust.

Session 5: Applications in Medicine and Proton Therapy / 15

Proton tracking for medical imaging and dosimetry

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For many years, silicon micro-strip detectors have been successfully used as tracking detectors for particle and nuclear physics experiments. A new application of this technology is to the field of particle therapy where radiotherapy is carried out by use of charged particles such as protons or carbon ions. Such a treatment has been shown to have advantages over standard x-ray radiotherapy and as a result of this, many new centres offering particle therapy are currently

under construction including two in the UK. The characteristics of a new silicon micro-strip detector based system for this application will be presented. The array uses specifically designed large area sensors in several stations in an x-u-v configuration to be suitable for very fast proton tracking with minimal ambiguities. The sensors will form a tracker capable of giving information on the path of high energy protons entering and exiting a patient allowing proton computed tomography (pCT) to aid the accurate delivery of treatment dose with tuned beam profile and energy. The tracker will also be capable of proton counting and position measurement at the higher fluences and full range of energies used during treatment allowing monitoring of the beam profile and total dose. Results with the delivered sensors will be presented along with details of the proposed readout electronics together with simulation work from GEANT4. Radiation tests and studies with different electronics at Clatterbidge Centre for Oncology and the higher energy proton therapy facility of iThemba Labs in South Africa will also be shown.

Session 5: Applications in Medicine and Proton Therapy / 125

Precise on-line position measurement for particle therapy

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Introduction
Field of particle therapy proved to be very effective for cancer treatment all over the world. At the Paul Scherrer Institute (PSI) Gantry 2 is a therapy delivery system which operates using proton beams of energies ranging from 70 MeV to 230 MeV [1]. Gantry 2 employs an active spot scanning technique which allow following the tumour shape by means of the fast energy change scanning in depth and two sweeper magnets which deflect the proton beam to a required position in a plane perpendicular the beam direction (lateral plane). Gantry 2 offers beams with dose per spot changing over three orders of magnitude. Beam size can vary from 2 mm to over 1 cm. The precision of the dose delivery in depth depends on the energy selection accuracy and description of the propagation medium. The homogeneity of the delivered dose distribution directly depends on the lateral position accuracy, thus the signal of any provided parameters must be reconstructed with sub-millimeter precision. In order to verify a reliable high quality patient treatment the on-line dose and position monitoring of the proton beam during the treatment as well as regular stability checks are of highest importance for the Quality Assurance (QA).
Method
There are many different methods available which can be used for lateral position verification with highest position resolution at single particle count level. However, in a case of particle therapy for on-line position verification the detector has to be placed right in the beam and, as a consequence, has to have possibly low material budget in order to reduce the multiple scattering during the beam delivery. Using the experience of the Gantry 1 therapy system [2] Gantry 2 chooses an ionization strip chamber for the on-line lateral position verification which is installed in the gantry nozzle[1]. This chamber covers the full scanning area with two perpendicular planes of 88 and 128 strips and a strip size of 2 mm. The strip chamber is equipped with advanced readout electronics which transfer the data to the therapy verification system. Spot position is propagated to the iso-center taking into account the Gantry 2 beam optics and cross-checked with an expected value within one millisecond time.
Apart from on-line position monitor an ionization strip chamber of the same type is used for regular position cross-checks. In addition to that, two smaller strip chambers with active area of 7 by 7 cm and strip size of 2.2 mm are used for the daily verification of the beam size, position and direction.
Results
A position deviation of more than one millimeter can lead to a dose fluctuation of several percents; therefore the required position precision has to reach the sub-millimeter level. The Gantry 2 strip monitor allows an on-line position and shape control of the full range of beams available at our machine with sub-millimeter precision. Signals varying from a high-weighted spots till lowest dose used by our therapy planning system (order of tenth of a milligray) can be reconstructed with the

required precision level due to the low detector noise. The detector granularity of 2 mm allows the same reconstruction precision for all spot sizes produced by Gantry 2 beams. The daily QA routine which is performed prior the patient treatment verifies the precision and stability of the delivered beam for the whole scanning area.

Conclusions & Outlook

The strip ionization chambers have proven to be an appropriate verification and QA tool for the scanning proton beam therapy system. Its suitable design allowed operating in a simple, efficient and extremely stable way over several years. The system demonstrates a sub-millimeter precision of the position reconstruction which is needed for dose homogeneity of better than 1% to guarantee a patient treatment quality at the highest achievable level. However, the sector of beam delivery technologies is developing and the design of the position detector could require further improvements using a lower material budget, different detector strip size or improved read-out electronics.

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Session 5: Applications in Medicine and Proton Therapy / 82

CMOS Active Pixel Sensors as Energy-Range Detectors for Proton Computed Tomography

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Proton therapy is gaining importance in the field of radiotherapy because of its potential of conforming the planned dose accurately at different depths defined and controlled by the proton energy, while sparing surrounding healthy tissue. The use of proton therapy for cancer treatment makes the need for developing new and more accurate imaging modalities for treatment planning, based on the direct measurements of tissue stopping power instead of tissue density, as in conventional X-ray Computed Tomography (CT). Since the first proof of concept in the early 70s, a number of technologies have been proposed to perform proton CT (pCT), as means of mapping tissue stopping power for more accurate treatment planning.

The basic requirements for pCT lie in measuring position and direction of individual protons, assess their residual energy in an energy-range detector to infer the most likely path in the patient and the energy deposited. In this way, the stopping power may be calculated along the inferred path. Previous prototypes of energy-range detectors for pCT, are based on the use of scintillator-based calorimeters that measure proton residual energy. However, such approach is limited by the need of a single proton passing through the energy-range detector per read-out cycle. A novel approach to this problem could be the use of pixelated detectors, where the independent read-out of each pixel can simultaneously provide the residual energy of a number

of protons in the same read-out cycle, facilitating a faster and more efficient pCT scan. The use of a stack of CMOS Active Pixel Sensors (APSs) as energy-range detector allows to infer residual proton energy by measuring the position where the proton stopped, provided that proton trajectories across the stack of APSs can be accurately tracked.
The feasibility of using a stack of APSs as energy-range detectors for pCT will be presented. Measurements, performed at the MC40 cyclotron at the University of Birmingham (36 MeV protons) and at iThemba LABS in South Africa (190 MeV protons), based on the use of a stack of two large area APSs, will be shown as proof of principle for proton tracking in an energy-range telescope. Monte Carlo simulations using the GEANT4 simulation toolkit, will also be presented to assess the efficiency of the tracking algorithm and the energy-range calibration. The required detector specifications for such a range telescope will also be discussed. The proposed design for a large area and fast read-out CMOS APS for pCT, developed by the Proton Radiotherapy Verification and Dosimetry Application (PRaVDA), consortium will be presented.

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A proton Computed Tomography based medical imaging system

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Proton radiation therapy is one of the most precise techniques for conformal radiation therapy in the treatment of cancer. One of the aspects that limits this medical approach is the relatively low accuracy of the stopping power (SP) maps inside the tissue, which are required for treatment planning and patient positioning, that today are derived from X-ray CT scans by converting the relative absorption coefficient ("Hounsfield values") to relative SP. In this framework proton Computed Tomography (pCT) is an imaging technique based on the use of proton beams with kinetic energies of the order 200 MeV to directly and precisely measure SP distributions.
A pCT system which aims to improve the accuracy on the SP map with respect to the ones obtained by conventional X-ray CT should be able to, at least, partially overcome the problems introduced by the intrinsic effect of the Multiple Coulomb Scattering on charged particles crossing matter. A viable solution to this problem is to measure the trajectory of each single proton both upstream and downstream the object under test. Furthermore the residual kinetic energy of the proton completes the 'single event' information. Having measured the trajectory entry and exit points and directions the most likely proton internal path (MLP) could be estimated. Assigning the proton energy loss to each single MLP an initial measurement data set can be constructed to be converted into 3-dimensional SP maps using tomographic reconstruction algorithms.
Subject of this talk will be the description of the pCT scanners developed by the INFN PRIMA/RDH collaboration which are based on a tracker and a calorimeter to measure single protons trajectory and residual energy, respectively. The tracker is composed by four x-y planes of silicon microstrip detector. Residual energy is measured by a calorimeter composed by YAG:Ce scinitillating crystals.

A first prototype of pCT scanner, with an active area of about 5x5 cm^2 and a data rate capability of 10 kHz, has been constructed and characterized with 60 MeV protons at Laboratori Nazionali del Sud – Catania (Italy) and with 180 MeV protons at Svedberg Laboratory – Uppsala (Sweden). Results of these measurements, including tomographic reconstructions and radiographies of test phantoms, will be shown and discussed.
To enter in a pre-clinical test phase the collaboration has designed a new pCT scanner with an extended field of view (up to ˜ $5x20^2$cm) and an increased event rate capability up to one MHz. This system will make use of the same technologies of the small one with an improved architecture to cope with the new requirements in terms of event rate and detector complexity. This pCT system, presently under construction, will be also described.

Session 6: Applications in High Energy Physics / 131

(Invited) Micromegas Detectors for the Muon Spectrometer Upgrade of the ATLAS Experiment

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The Micromegas (MICRO MEsh GAseous Structure) chambers have been proven along the years to be reliable detectors with excellent space resolution and high rate capability. Large area Micromegas will be employed for the first time in high-energy physics for the Muon Spectrometer upgrade of the ATLAS experiment at CERN LHC. A total surface of about 150 m^2 of the forward regions of the Muon Spectrometer will be equipped with 8 layers of Micromegas modules. Each module covers a surface from 2 to 3 m^2 for a total active area of 1200 m^2. Together with the small-strips Thin Gap Chambers, they will compose the two New Small Wheels, which will replace the innermost stations of the ATLAS Endcap Muon tracking system in the 2018/19 shutdown.
The principles of operation and recent developments of this type of Micro Pattern Gas Detector will be reviewed, along with our plans towards the construction of the modules, which will take place in several production sites. An overview of the detector performances obtained in the recent years test beam campaigns with high energy particle beams at CERN will be also presented, together with examples of applications of this technology to fields beyond particle physics.

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Physics Studies for the CMS Muon System Upgrade with Triple-GEM detectors

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The CMS collaboration considers upgrading the muon forward region with Gas Electron Multiplier (GEM) chambers, which are able to handle the extreme particle rates expected in this region along with a high spatial resolution. This allows to combine tracking and triggering capabilities, resulting in a lower trigger threshold along with improved muon identification and the track reconstruction. In the last year the GEM project took a major leap forward by integrating triple-GEM chambers in the official CMS software, allowing physics studies to be carried out. Several benchmark analyses have been studied for the impact of such detector upgrade on the physics performance. The contribution will review the status of the CMS upgrade project with the usage of GEM detector, discussing the trigger, the muon reconstruction performance and the impact on the physics analyses.

Session 6: Applications in High Energy Physics / 27

The XENON program: performances of the XENON100 detectors and development of the new detector XENON1T

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The aim of the XENON program is to search for dark matter particles through their interaction in an ultra-pure medium. A favourite dark matter candidate are the so-called WIMPs, which can be detected via their elastic scattering off Xenon nuclei. The XENON dark matter program consists in operating and developing 3-D position-sensitive double-phase time projection chambers (TPCs) using ultra-pure liquid Xenon as both target and detection medium by employing an increasing fiducial target mass scale. The ability to localise events within millimetre resolution, enables to minimise the background by selecting events in the fiducial volume and exploiting the self shielding property of Xenon. The current phase of the project is the XENON100 detector with 160 kg of liquid Xenon, located deep underground in the Gran Sasso National Laboratory (LNGS), in Italy. We will give an overview of the XENON100 detector performances, describing in detail the energy and position reconstruction. We will present also the adopted improvements for the next detector, XENON1T, currently under construction at LNGS, that will host 3.3 tonnes of ultra-pure liquid Xenon.

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Large size hybrid GEM-Micromegas gaseous detectors for high particle flux at COMPASS

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Large size Micromegas gaseous detectors (40x40 cm^2 active area) are being developed in view of the forthcoming COMPASS experiment new physics programs which will use the CERN-SPS high intensity muon and hadron beams of a few hundred GeV scattered on thick fixed targets. The detectors have to be active also in the beam area, where intensities as high as a few hundred of kHz/mm^2 are expected, with the same performances (96% efficiency, spatial resolution better than 100 μm).
In such a hot environment, with highly ionizing particles, spark generation is a major issue for MPGD detectors. We will show studies on two different technics used to reduce the park rate in presence of high particle flux. The first one is the use of a specific resistive layer on the read-out board, namely the *buried resistor* technology. The second one is the adding of a pre-amplifying GEM foil to a non-resistive Micromegas detector, leading to an *hybrid* detector. Comparative tests done in real beam conditions and in production environment will be presented. The very promising results obtained with the hybrid detectors lead to the finalization of the design using this technology. The aspect of the industrialization of the fabrication process will also be presented. The achievement of transferring to the industry the delicate technology of making *bulk* Micromegas boards (monolithic assembly of a micromesh and a board) for large size,

low budget material, and complicated printed circuit drawing with vias at very small pitches, is also a great success.

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Charge Collection Efficiency Simulations of Irradiated Silicon Strip Detectors

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Position sensitive silicon detectors are largely employed in the tracking systems of High Energy Physics (HEP) experiments due to their outstanding performance. They are currently installed in the vertex and tracking part of the CMS experiment at LHC the world's largest particle physics accelerator at Centre for European Nuclear Research (CERN), Geneva.
An upgrade of LHC accelerator is already planned, namely the high luminosity phase of the LHC (HL-LHC foresee for 2023). The tracking system of CMS at HL-LHC will face more intense radiation environment than the present system was designed for. This requires the upgrade of the full tracker that will be equipped with higher granularity as well as radiation hard sensors, which can withstand higher radiation levels and higher occupancies. In order to address the problems caused by intense radiation environment extensive measurements and simulations studies requirements have been initiated for investigating different designs and materials options for Si micro-strip sensors.
The simulation studies of silicon detectors, based on commercial packages (Silvaco and Synopsys TCAD), are performed in order to investigate sensor characteristics before and after irradiation for fluences up to 1.5×10^15 neq cm−2.
Essential information of the performance of an irradiated silicon detector is obtained by monitoring its Charge collection efficiency (CCE). From the evolution of the CCE as a function of fluence it is possible to directly observe the effect of the radiation induced defects to the ability of the detector to collect charge carriers generated by traversing minimum ionizing particles (mip).
The talk covers the numerically simulated CCE and CCE loss between the strips of irradiated silicon strip detectors using Synopsys Sentaurus package. A two level and non-uniform three level defect models were applied for the proton irradiation simulations and two level model for neutrons. The results are presented together with measured CCE of Hamamatsu Photonics K. K. produced strip detectors irradiated by different particles and fluences. Simulated CCE is simply defined as the ratio of the charge collected by an irradiated detector to the collected charge of a non-irradiated detector. CCE simulations included both n-in-p and p-in-n silicon strip detectors. Simulations were done in 2D and the third dimension was taken into account by an area factor. As for the measurement of real detectors, the simulation temperatures were RT for non irradiated and -20C for irradiated devices. Irradiation was simulated by 1 MeV neutron equivalent fluences, ranging from 10^{14} to 1.5×10^{15} cm−2. Also the significant increase of surface damage with fluence was considered in proton irradiated detectors. This required the application of the non-uniform 3-level defect model to maintain the experimentally observed strip isolation in n-on-p detectors. Simulated charge was injected either by a mip or IR laser. The experimentally observed CCE loss between the strips was simulated by first varying the position of charge injection from the middle of the pitch to the center of the strip. Then the CCE loss was determined as the ratio of the difference in the collected charge at the center of the strip and in the middle of the pitch to

the charge collected at the strip. Simulations were then compared with the CCE measurements done with Silicon Beam Telescope (SiBT) and ALiBaVa setup.
Results show considerable agreement with measurements in both CCE and its position dependency. By being able to verify experimental results, the numerical CCE simulations are proven to have also predictive power. This can lead to reduced time and cost budget in the R&D of the novel silicon radiation detector designs with upgraded radiation hardness.

Session 7: Engineering and Environmental Imaging / 133

(Invited) Industrial imaging using high energy photons

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The importance of advanced imaging modalities in modern medicine is widely appreciated. Probably less familiar is their potential use for studying engineering processes in industry. This is especially true of techniques based on the use of high energy photons which can penetrate metal casings. Transmission imaging can distinguish individual phases in multi-phase flow, while the use of radioactive tracers (in SPECT or PET) reveals more subtle differences and provides some dynamic information. By tracking radioactive particles (in RPT or PEPT) velocity fields can be mapped. This paper will briefly present examples of all these techniques and consider some of the opportunities and challenges for industrial imaging using high energy photons.

Session 7: Engineering and Environmental Imaging / 83

Environmental Compton camera development: imaging radionuclide transport in soils and geomaterials

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Current research in the Nuclear Instrumentation group of the University of Liverpool focuses on the optimisation of the gamma ray Compton camera [1]. Such an imaging system can utilise two energy and position sensitive semiconductor detectors with the Compton scattering formula to gain position and energy information of gamma-ray emitting radioactive sources. This presents a significant improvement in efficiency and dynamic range over coded aperture systems currently used in industry [2]. We present the progress of a project funded by the Natural Environment Research Council, aiming to optimise a Compton camera system for environmental radioactivity measurements. The project will investigate the feasibility of a range of applications, from small scale imaging of radiation transport through soil and uptake in plants, to large scale monitoring of soil erosion and radioisotope retention in tree canopies. This will build upon previous work that developed the proof of concept of a fused radiometric and optical stereoscopic imaging system for use in nuclear decommissioning.
This project employs a Compton camera that consists of two planar HPGe semiconductor detectors of dimensions 60x60x5 mm and 60x60x20 mm. The processes of radiometric image generation will be presented in the context of an experiment that imaged 20 MBq Cs-137 point sources at standoff distances of 0.8–1.5 m. The merits of a new iterative image reconstruction algorithm will be demonstrated that gives significant improvements in image resolution over analytical methods. Experiments will now focus on the ability of the system to image low activity sources

and initial measurements will look to develop previous work by Corkhill et al [3] that produced time lapse images of Tc-99m transport using a gamma camera. A liquid Ce-139 source will be dripped through a column of sand and the Compton camera used to monitor flow, with the aim of enabling detailed quantification of radionuclide reactive transport in a wide range of wastewater filtration and environmental scenarios. This will be presented alongside GAMOS [4] simulations that investigate the limits of the system. The potential for fusion with optical stereoscopic images will be discussed alongside prospects for this project beyond the laboratory work.

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Session 7: Engineering and Environmental Imaging / 93

Adaptive response matrices for optimised mixed-field imaging

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Pinpointing the location of radiological materials has the potential to be extremely useful in many scenarios, not least of which is in nuclear decommissioning. This subject forming the focus application of this research. We present a compact and lightweight mixed-field imaging system able to produce images of radiation source terms distributed in a local environment, passively and in near real-time. A tungsten collimator produces a weighted spatial sensitivity of a liquid scintillation detector which is efficient at detecting both gamma rays and fast neutrons. Moderation of neutrons is not required, allowing the principle of back-projection to be applied to the detected neutrons as well as gamma rays. This position-sensitive detector is then rotated sequentially through two axes to collect raw image data from a minimum of 2π steradians. Radiation events are discriminated in real-time by a mixed-field analyser unit using a pulse-gradient analysis algorithm programmed into the firmware of an FPGA. Upon the collection of raw data, an algebraic reconstruction algorithm is used to reconstruct two independent images of fast-neutron and gamma-ray emitters in the surroundings. This allows these source terms to be identified and located when coupled with a corresponding overlaid optical image. A key component in this image reconstruction is a large system matrix (containing tens of thousands of elements) which maps the sensitivity of the collimated detector to all surrounding space, for each data collection position. This system matrix is dissimilar for each radiation type due to the different interaction behaviours pronounced by the fundamental differences between gamma rays and neutrons. Further, the system matrix is also highly dependent on the energy spectrum of each radiation source; the optimal system matrix for image reconstruction will therefore be specific to each scenario, depending on the isotopes present in each case. Measuring these values experimentally to high precision is incredibly time-consuming, inconvenient for complex fields, and could invoke large costs. In response we make use of a Monte Carlo radiation transport code, validated strategically against experimental data to define these system matrices for a given energy distribution and to facilitate the most accurate image solutions. The resulting images gain superior resolution through this method, allowing an improved characterisation of radiological hazards in an environment.

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Digital fast neutron radiography of rebar in concrete

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Neutron imaging has previously been used in order to test for cracks, degradation and water content in concrete. However, these techniques often fall short of alternative non-destructive testing methods, such as[U+F067]gamma-ray and X-ray imaging, in terms of resolution. Further, they can be compromised by the significant expense associated with thermal neutron sources that can often precipitate the need for a reactor which is clearly not portable in the context of the needs of field applications. This paper summarises the results of a study to investigate the potential for transmission radiography based on fast neutrons, in order to determine the presence of heterogeneities in concrete structures such as reinforcement structures, by assessing any variation of transmitted flux between structures containing different materials. Monte Carlo simulations have been performed and the results from these are compared to those arising from practical tests using a 252Cf source. The experimental data have been acquired in real-time using a digital pulse-shape discrimination system that enables fast neutron transmission to be studied across an array of liquid scintillators placed in close proximity to samples under test, and read out in real time. This approach could offer non-destructive testing methods that give less dose, better transportability and better accessibility than other methods previously used for this purpose that are suitable for thick samples where gamma-ray and X-ray methods can be limited.

Session 8: Detectors for Synchrotrons and FELS / 135

(Invited) Jungfrau, Mönch and Eiger: Detector Development at the Swiss Light Source

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The detector group at the Swiss Light Source (SLS) is currently involved in several detector development projects both for synchrotrons and XFELs. In the presentation we give an overview of our developments with a focus on Jungfrau, Mönch and Eiger. Eiger is a state of the art single photon counting detector whereas Jungfrau and Mönch are charge integrating systems which overcome several limitations of today's single photon counting detectors like count rate capability, pixel size or low energy limit.
Eiger is a single photon counting pixel detector with a pixel size of 75 micron and a focus on high frame rates (up to 24 kHz). We are currently working on the assembly of a 9M pixel detector, the installation at the CSAXs beamline of the SLS is foreseen for this year.
Jungfrau is a charge integrating detector with a 75x75 µm2 pixel size, dynamic gain switching, a noise of about 120 electrons and a dynamic range of 104 photons per pixel and image. The detector is developed for SwissFEL (the XFEL currently being built at the Paul Scherrer Institut). However, with a frame rate of 1-2 kHz and a data quality similar to single photon counting detectors, it is also an excellent detector for applications at synchrotrons specifically those having a high photon rate (like protein crystallography or small angle scattering). We plan various system sizes ranging from single modules, having about 500k pixels and an active area of 4 x 8 cm2, up to a 16M detector consisting of 32 modules covering an area of 32cm x 32cm.
Mönch is also a charge integrating detector with a pixel size of 25 µm. It is currently in a research state, we have first prototypes and work on defining larger systems. The current prototype chip has 160 x 160 pixels. Since the possibility of interpolating between neighboring pixels allows a

micrometric resolution the main application is high resolution x-ray imaging both at synchrotrons and with x-ray tubes. It also has a very low noise of about 30 electrons allowing measurements with single photon resolution down to about 400eV.
The status of the systems, performance characteristics, first results, applications and the plans for the future will be shown.

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PERCIVAL: Design and Characterisation of a CMOS Image Sensor for Direct Detection of Low-Energy X-Rays

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PERCIVAL (Pixelated, Energy Resolving CMOS Imager, Versatile And Large) is a wafer-scale, CMOS imager under development at Rutherford Appleton Laboratory (RAL; Didcot, UK) in collaboration with Deutsches Elektronen-Synchrotron (DESY; Hamburg, Germany), Elettra – Sincrotrone Trieste (Trieste, Italy), and Diamond Light Source (DLS; Didcot, UK).
PERCIVAL is designed for high-speed and low noise detection of soft X-rays to address the growing need for such sensors in the FEL and synchrotron research areas. It is based on a novel 27μm pitch, high dynamic range pixel, designed in a 0.18μm standard CMOS image sensor process. Specifications for the final sensor are noise below 15e-, 20 bits dynamic range, and a continuous frame rate of 120Hz with digital correlated double sampling. The sensor will be Back-Side Illuminated (BSI) in order to achieve quantum efficiency in excess of 90% in the primary energy range of $0.25 - 1$ keV.
The need for a high pixel resolution led to a stitched design, allowing the manufacture of large-area sensors with seamless boundaries. The final sensors will be made of repeated unity block that can be stitched to give a variety of sensor sizes. The first version of the Percival sensor will be comprised of a 1408 x 1484 array, with a second PERCIVAL sensor arriving later in a 3528 x 3717 configuration, using the full size of a 200mm CMOS wafer. With both versions a 2x2 cloverleaf module will be possible.
The pixel allows for in-pixel adaptive gain switching between the diode and three capacitors of increasing size. This gives single photon discrimination at low flux, while retaining the capability to measure higher flux when required at the cost of increased noise. Four sample readings are taken while only the result from the highest-required gain mode is then converted by the on-chip, column-parallel, 12-bit ADC. Both reset and signal frames are sampled, allowing for off-chip, or digital, Correlated Double Sampling (CDS). This is then passed through a high-speed serialiser, and read out over LVDS lines, giving a final data rate of over 50Gb/s.
The final sensor is currently being designed; we will present results from test structures undergoing optical and X-ray characterisation for both Front Side Illuminated (FSI) and BSI sensors. The method of optical characterisation to be discussed is based on the Photon Transfer Curve (PTC), derived from integration sweeps using a calibrated, uniform light source of known wavelength. The X-ray tests performed were using an Iron-55 source of known activity. This allows for corroboration of the gain results from the PTC, as well as a measure of the noise based on the spread of the Gaussian peaks from the primary emission K-alpha and K-beta X-rays.

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The Large Pixel Detector for the European XFEL

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We present an overview of the Large Pixel Detector (LPD), results from beam tests and the next steps and plans for future developments. LPD is a large area megapixel scale detector primarily designed for the European XFEL (XFEL.EU). At XFEL.EU the LPD detector must be capable of operating with a frame rate of 4.5MHz and record images with a dynamic range of 1:100,000 photons whilst maintaining low noise. The LPD system has a large in pixel memory depth of 512 images that can be selected with a flexible veto system. Data is then transferred off the detector head in between x-ray pulses with an accompanying high rate data acquisition system (˜10 GB/s). The system is assembled from custom silicon sensors and ASICs as well as a programmable data acquisition cards and supporting electronics and mechanics. A prototype LPD system has been constructed and tested on a range of beam lines including the free electron laser, LCLS. The highlights of these tests will be reported.

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AGIPD, a high dynamic range fast detector for the European XFEL

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AGIPD - (Adaptive Gain Integrating Pixel Detector) is a hybrid pixel X-ray detector developed by a collaboration between Deutsches Elektronen-Synchrotron (DESY), Paul-Scherrer-Institut (PSI), University of Hamburg and the University of Bonn. The detector is designed to comply with the requirements of the European XFEL, 4th generation free electron laser source being constructed in Hamburg, Germany. The key features of the XFEL will be the high brilliance pulses with a tight bunch structure. It is expected that the source will produce short (˜100 fs), highly coherent pulses with a peak brilliance of 1033 ph/(s mm2 mrad2 0.1%BW) in the energy range 0.3 – 25 keV (depending on the experimental station). The pulses will be organized in

bunch trains with a frequency of 10 Hz. Each bunch consists of 2700 pulses with > 1012 photons of 12keV each separated by a 220 ns resulting in 4.5 MHz pulse frequency. Such a characteristics of the source put severe requirements on the detector readout electronics. The radiation tolerant Application Specific Integrated Circuit (ASIC) is designed with the following highlights. High dynamic range: from single photon sensitivity up to 104 12.5 keV photons, achieved by the use of the dynamic gain switching technique between 3 possible gains of the charge sensitive preamplifier. In order to store the image data ASIC incorporates 352 analog memory cells per pixel, allowing also to store corresponding gain bits (3 voltage levels). It is operated in random-access mode at 4.5 MHz frame rate. An external vetoing signal may be used to force the acquisition system to overwrite "bad" frames during the acquisition. The data is transferred then to the DAQ system and digitized during the 99.4 ms between the bunch trains. The AGIPD has a pixel area of 200x200 μm2, a 500 μm thick silicon sensor is used. The full 1M pixel system will contain 4 quadrants of 4 modules each. 1 module consists of a single module sensor bump-bonded to 16 full scale chips.
Since the beginning of the project 5 prototype ASICs were manufactured and tested in order to prove the architecture principals and measure the characteristics. Extensive sensor wafer testing is done. The mechanical concept developed in the close contact with the XFEL beamline scientists and now is being produced. Presented will be a project design and it's highlights with a corresponding measurements along with the experimental results achieved with the latest full scale ASIC "AGIPD 1.0" available.

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Development and characterisation of sensor prototypes for the BELLE II Pixel Detector

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The B-factory KEKB in Japan is currently being upgraded to SuperKEKB. It will reach a world record luminosity of 80×10^{34} cm^{-2}s^{-1}, i.e. 40 times larger than the world record value previously achieved at KEKB. The upgrade program involves a major modification of the Vertex Detector (VXD), with the insertion of two additional Pixel Detector (PXD) layers located between the beam pipe and the four Double Sided silicon Strip Detector (DSSD) layers.
The sensor of choice for the PXD is the Depleted p-channel Field Effect Transistor (DEPFET), organised in a matrix. DEPFETs are pMOSFETs integrated on a highly resistive, fully depleted n-type substrate, with a p^{+}-type backside contact. An n-type deep implant under the gate, named internal gate, modulates the current, while an adjacent n^{+}-type contact works as a reset mechanism. DEPFETs offer internal amplification, a very small output capacitance, a high Signal to Noise Ratio (SNR) even at room temperature and very low power consumption.
The increased background at SuperKEKB requires fast readout in order to keep the occupancy small. Hence, a high frame rate of 50 kHz is guaranteed by a four-fold multiplexed readout. A small thickness of 75 μm, for multiple scattering reduction, is achieved using cutting edge SOI technology. Three different ASICs, bump bonded on the same silicon substrate, allow the activation and reset of the pixels (SWITCHER), digitisation of the current (DCD) and processing and synchronisation (DHP).
Current developments involve the production and characterisation of a technology-prototype, named Electrical Multi Chip Module (EMCM). With the EMCMs, variations of the metal-dielectric layers needed for control, signal and power lines routing can be studied in detail, which allows the choice of the optimal technology. Moreover, the EMCM represents also a tool for in-depth testing of the control and readout electronics. The innovative and challenging characterisation method of this technology-prototype and the achieved results will be described, along with details on its development. The latest production of the final sensor and its characterisation concept will be also presented.

Session 9: Applications in Astronomy and Space Science / 18

(Invited) DEPFET detectors for applications in astrophysics and photon science

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DEPFET detectors for applications in astrophysics and photon science
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The DEPFET (DEpleted P-channel FET) is a combined detector-amplifier structure suitable for a wide range of applications. It has outstanding properties, like excellent energy resolution, high readout speed, low noise, charge storage for readout on demand and low power consumption which is highly valuable for space applications. Due to its versatile design options, the DEPFET pixel can be tailored to meet the specific experimental requirements, for example the pixel size can be easily adjusted by design to the optics point spread function. Advanced developments of specialized DEPFET pixel designs provide various new capabilities, like DEPFETs with a tunable non-linear amplification, others with intrinsic electronic shutter or sub-electron noise, and a new concept to minimize deadtime.
Detectors based on DEPFET technology are now considered for and implemented in projects in the fields of astrophysics (BepiColombo, ATHENA), photon science (European XFEL) and high energy particle physics (BELLE-II). In the following, the DEPFET developments for the projects EuXFEL and the MIXS instrument on BepiColombo will be discussed
Photon Science: One of the X-ray imaging detectors which is currently developed for the European XFEL is the DSSC (DEPFET Sensor with Signal Compression). The detector is optimized for photon counting at low X-ray energies and designed to operate at frame rates up to 4.5 MHz. For XFEL, the DEPFET design was customized in such way, that the DEPFET has intrinsic non-linear signal amplification in order to provide high dynamic range with simultaneous single photon resolution for low-energy X-ray photons. The full sensor will have 1024x1024 pixel and is subdivided into an array of 32 sensor chips with 128x256 pixel each. The size of the hexagonal pixels is 204x236 μm^2.
Planetary Science: The Mercury Imaging X-ray Spectrometer (MIXS) is a two-channel instrument on board of the 5th ESA cornerstone mission BepiColombo, dedicated for imaging x-ray spectroscopy of the Mercury surface. The detector plane arrays (DPA) for the energy and spatial resolved detection of x-rays are based on DEPFET (Depleted P-channel FET) macropixel detectors with each 64x64 pixel and 300x300 μm^2 pixel size. The readout time for a full detector frame is 170 μs. The MIXS target energy band is from 0.5 to 7 keV with an energy resolution better than 200 eV at 1 keV at mission end, despite the harsh radiative environment. This allows to access the Fe-L line at about 0.7 keV, which was not accessible to previous instruments, and to separate the x-ray lines of the elements of interest. The flight grade DPAs are calibrated and now in the stage of implementation into the MIXS flight instrument. MIXS will be the first space borne instrument equipped with DEPFET detectors.

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High spatial resolution detector for at-wavelength metrology of X-ray optics

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Recent advancements in the field of X-ray astronomy have relied significantly on innovations in grazing incidence X-ray optics technology, especially for the hard X-ray range for energies above 10 keV. The behavior of these X-ray telescopes for current and planned astrophysical and solar imaging missions needs to be well understood, and fully characterizing the optics includes measurement of the point spread function (PSF) and effective area as a function of energy for flight optics as well as understanding the scattering and reflectivity properties of substrate coatings. This requires unique, very high spatial resolution, high sensitivity, photon counting and energy discriminating, large area detectors. We report on the development of a detector that is well suited to meet these requirements. A prototype version of this camera was used to calibrate the X-ray focusing optics for the Nuclear Spectroscopic Telescope Array (NuSTAR) mission successfully launched in June 2012. The key piece of the detector is a high spatial resolution electron-multiplying charge-coupled device (EMCCD). The detector is back-thinned and optically bonded via a fiberoptic taper to a purpose-fabricated high resolution, high brightness CsI(Tl) scintillator with a microcolumnar structure. Here we present our recent work on the construction of the detector, scintillator development, production and testing as well as our software development efforts for single photon detection and energy discrimination. We will also present results from our final measurement campaign at an X-ray test facility at NASA's Marshall Space Flight Center (MSFC).

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A CMOS Active Pixel Sensor for high resolution imaging of the Jovian system

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The Jovian system is the subject of study for the Jupiter Icy Moon Explorer (JUICE), an ESA mission which is planned to launch in 2022. The scientific payload is designed for both characterisation of the magnetosphere and radiation environment local to the spacecraft, as well as remote characterisation of Jupiter and its satellites. A key instrument on JUICE is the high resolution and wide angle camera, JANUS, whose main science goals include detailed characterisation and study phases of three of the Galilean satellites, Ganymede, Callisto and Europa, as well as studies of other moons, the ring system, and irregular satellites.
The CIS115 is a CMOS Active Pixel Sensor from e2v technologies selected for the JANUS camera. It is fabricated using 0.18 μm CMOS imaging sensor process, with an imaging area of 2000 x 1504 pixels, each 7 μm square. A 4T pixel architecture allows for efficient correlated double sampling, improving the readout noise to better than 8 electrons rms, whilst the sensor is operated in a rolling shutter mode, sampling at up to 10 Mpixel/second at each of the four parallel outputs.
JANUS will face an extremely hostile radiation environment and it is essential to understand how this will impact the performance of the CIS115. During the interplanetary travel phase of the mission it will be exposed to solar protons and cosmic rays and once it arrives in the Jovian system it will face continual bombardment by protons and high energy electrons trapped within Jupiter's magnetic field. To ensure that the CIS115 will meet the mission's science data collection requirements a detailed radiation damage study is planned which will include gamma, proton, heavy ion and electron irradiations. In addition to the long-term degradation of the CIS115's performance, the effect of the trapped environment around Jupiter on the sensor must be studied to confirm that background radiation during observation will not significantly degrade the image quality. The latest results of this analysis and the CIS115's radiation campaign will be presented.

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Detector concepts for wide field X-ray imaging using Lobster Eye microchannel plate optics

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Microchannel plate x-ray optics is an emerging technology, recently space proven on the NASA DXL sounding rocket experiment and soon to fly on the ESA Bepi-Colombo mission to Mercury. This compact, light-weight technology enables wide field of view x-ray imaging by mimicking the structure of a lobster's eye; MPOs utilise grazing incidence reflections within the high aspect ratio square section pores of a curved microchannel plate to focus x-rays over a wide angular range on to a focal plane detector.
We describe the detector requirements for the proposed Einstein Probe (EP) mission, a small scientific satellite dedicated to time-domain high-energy astrophysics. EP will utilise a very large field of view MPO for discovery of high-energy transients and to monitor variable objects at x-ray energies in the range 0.5-4 keV. The mission requires an array of large format soft x-ray imaging detectors with moderate spatial and energy resolution.
We discuss the detector options available and the trade-offs in terms of performance, cost effectiveness, required resources and operational risks for the 5+ year mission. We present results and simulations from the detector development undertaken during the mission advanced study phase.

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Particle tracking at cryogenic temperatures: The Fast Annihilation Cryogenic Tracking (FACT) detector for the AEgIS antimatter gravity experiment

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The AEgIS experiment at Cern is an interdisciplinary collaboration between atomic, plasma and particle physicists, with the scientific goal of performing the first direct measurement of the Earth's gravitational acceleration on antimatter. The principle of the experiment is as follows: cold antihydrogen atoms are synthesised in a Penning-Malberg trap and are Stark accelerated towards a moire deflectometer, the classical counterpart of an atom interferometer, and annihilate on a position sensitive detector. Crucial to the success of the experiment is an antihydrogen detector that will be used to demonstrate the production of antihydrogen and also to measure the temperature of the anti-atoms and the creation of a beam. The operating requirements for the detector are very challenging: it must operate at close to 4K inside a 1T solenoid magnetic field and identify each of the annihilation vertices of the hundred or so antihydrogen atoms that are produced during the 1ms period of antihydrogen production. Our solution - called the FACT detector - is based on a novel multi-layer scintillating fiber tracker with SiPM readout and an FPGA based readout system. This talk will present the design of the FACT detector and detail the operation of the detector in the context of the AEgIS experiment.

Session 10: Posters 1 (Particle Physics, Pixel Detectors and Lifesciences) / 30

Development of radiation hard silicon strip sensors using T-CAD simulations and comparison with subsequently produced detectors

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Position sensitive silicon detectors are largely employed in the tracking systems of High Energy Physics (HEP) experiments due to their outstanding performance. They are currently installed in the vertex and tracking part of the CMS experiment at LHC the world's largest particle physics accelerator at Centre for European Nuclear Research (CERN), Geneva. An upgrade of LHC accelerator is already planned, namely the high luminosity phase of the LHC (HL-LHC foresee for 2023). The tracking system of CMS at HL-LHC will face intense radiation environment than the present system was designed for. This requires the upgrade of the full tracker that will be equipped with higher granularity as well as radiation hard sensors, which can withstand higher radiation levels and higher occupancies. In order to address the problems caused by intense radiation environment extensive measurements and simulations studies requirements have been initiated for investigating different designs and materials options for Si micro-strip sensors. The simulation studies of silicon detectors, based on commercial packages (Silvaco and Synopsys T-CAD), are performed in order to investigate sensor characteristics before and after irradiation for fluences up to $1.5 \times 10^{15} n_{eq}/cm^2$. This work will demonstrate the development of radiation damage models for T-CAD studies and the subsequent simulations of new silicon sensor geometries. On the basis of the Hamamatsu Photonics K.K (HPK) measurement campaign data of irradiated silicon strip sensors, an effective two-defect model was developed in order to reproduce measurements after proton and neutron irradiation from 1×10^{14} n_{eq}/cm^2 up to 1.5×10^{15} n_{eq}/cm^2 respectively. After successful reproduction of data, new n-in-p sensor geometries have been simulated and studied on charge collection efficiency (CCE) and electrical breakdown behaviour. The most promising geometries have been designed and produced on a float-zone silicon wafer with Centro Nacional De Microelectronica (CNM) in Barcelona. The strip sensors have been irradiated to several fluences corresponding to the simulation input parameters and the HPK campaign and measurements have been done with the ALiBaVa fast read-out system based on the analogue Beetle chip. CCE results of the new sensors after irradiation are in good agreement with the CCE predicted by T-CAD studies with the Synopsys package as well as backplane capacitance and leakage current from measurements with probe needles. Hence the effective defect model is sufficient for investigations of new sensor designs in order to withstand the harsh radiation environment for the HL-LHC era. Furthermore, with T-CAD it is possible to access the electric field distribution in the bulk and to visualize possible hot spots which can not be directly investigated with experimental setups. This poster covers the development of the effective defect model for T-CAD simulation studies of new n-in-p technology sensors and the subsequent production of the sensors. The agreement of simulation and experimental data demonstrates that T-CAD studies represent a powerful tool for design studies of new radiation hard silicon detectors.

Session 10: Posters 1 (Particle Physics, Pixel Detectors and Lifesciences) / 42

Characterisation, calibration and performance of single photon counting CdTe pixel detectors

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The PILATUS3 CMOS ASIC with instant retrigger technology is compatible with CdTe sensors in electron collection mode. Applying a special shaper mode allows for the measurement of higher energy X-rays.
Pixelated CdTe sensors were bumpbonded to PILATUS3 CMOS readout ASICs. A large area detector of 16.8cm x 3.4cm was built consisting of four 1mm thick CdTe sensors with an area of 4.2cm x 3.4cm each, resulting in a CdTe detector with 200k pixels. Another detector was built with a single 750um thick CdTe sensor with an area of 4.2cm x 3.4cm. Both detectors were calibrated and trimmed for X-ray energies between 8keV and 60keV. The detectors were characterized in terms of energy resolution, long term stability at low and high X-ray fluxes, count rate behaviour, quantum efficiency and point spread function as a function of energy. The measurements were done with an X-ray tube setup and at a synchrotron beamline (PTB laboratory at BESSY II). The performance of both sensor types is compared.
The CdTe sensor material was investigated under different irradiation fluxes and X-ray energies in order to study polarisation effects, defects and non-uniformities, typically arranged in a network of lines in CdTe. Optimal operation conditions as a function of temperature and bias voltage have been investigated and are compared for both types of sensors. Comparing the 750um and the 1mm sensor showed that the thinner sensor is less affected by sensor polarisation and non-uniformities. Furthermore, a more negative bias voltage and a higher operation temperature have a positive influence on both effects.

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Low-area trim DAC in 40nm CMOS technology for pixel readout chips used in hybrid detectors.

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The recent directions of development in hybrid pixel detectors working in single photon counting mode are nanometer or 3D technologies that support the trend of making pixels smaller and more functional at the same time. Usually single pixel in readout electronics for X-ray detection comprises of charge amplifier, shaper and discriminator that allow to classify events occurring at the detector as true or false hits by comparing obtained signal with threshold voltage, which minimizes the influence of noise effects. However, making the pixel size smaller often causes problems with pixel to pixel uniformity [1] and additional effects like charge sharing become more visible [2].
To improve channel-to-channel uniformity or implement an algorithm for charge sharing effect minimization, a small area trimming DAC working in each pixel independently is necessary [3]. However, meeting the requirement of small silicon area often results in poor linearity and even non-monotonicity of DAC [4]. In this paper we present a low-area monotonic thermometer-coded 6-bit DAC with novel binary-to-thermometer decoder.
Monte Carlo simulations were performed on the design proving that under all conditions designed DAC is inherently monotonic. Presented DAC was implemented in the 40nm CMOS technology in the prototype readout chip with 432 pixels working in single photon counting mode, with two trimming DACs in each pixel. The area of single 6-bit DAC is about 28 μm x 10 μm. Measurements and chips' tests were performed to obtain reliable statistical results covering temperature and range characterization of the DACs, together with the tests with X-ray radiation.
This work was supported by National Science Center, Poland under Contract DEC-2011/01/B/ST7/05155
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Testing fully depleted, thick monolithic CMOS pixels with high quantum efficiency

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The Centre for Electronic Imaging (CEI) has an active programme of evaluating and designing CMOS image sensors with high quantum efficiency for applications in near-infrared and X-ray photon detection. This paper describes the performance of devices made on a high resistivity 50µm thick substrate with a particular focus on determining the depletion depth and the quantum efficiency. The test devices contain 8x8 and 16x16 pixel arrays using CCD-style charge collection and manufactured in a low voltage CMOS process by ESPROS Photonics Corporation.
The measurements of depletion depth will be completed as part of this study and involve a combination of semiconductor device modelling and measurements of the device Quantum Efficiency (QE). Knowledge of the theoretical depletion depth is also essential, so semiconductor models of the devices are produced using Silvaco TCAD. By biasing the devices over a range of voltages, the depletion depth will change, allowing QE models to be calibrated.

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Interconnect and bonding techniques for pixelated X-ray and gamma ray detectors

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In the last decade, the Detector Development Group at the Technology Department of the Science & Technology Facility Council (STFC), UK, established a variety of fabrication and bonding techniques to build pixelated X-ray and gamma ray detector systems such as the HEXITEC detector for imaging and spectroscopy [1]. The fabrication and bonding of such devices comprises a range of processes and techniques including material surface preparation, detector pixelation by means of photolithography, stencil printing, flip-chip and wire bonding of detectors to application-specific integrated circuits (ASIC). This paper presents interconnect and bonding techniques used in the fabrication chain for pixelated detector assemblies at STFC.

Individual detector dies (~20x20mm^2) and raw material such as cadmium zinc telluride (CZT) crystals can be cut with a diamond wire saw to the required thickness (usually 1mm to 5mm). Subsequently anode and cathode surfaces are lapped and polished to a mirror-finish. Electroless gold deposition and lithography are used for forming typically 74 x 74 arrays of 200 x 200 μm^2 pixels with 250 μm pitch on such prepared detector surfaces. Due to a lack of availability of CZT wafers, lithography is commonly carried out on individual detector dies which represents a significant technical challenge as the edge of the pixel array and the surrounding guard band lie close to the physical edge of the crystal. The fabrication of these detectors from single die is an important first step towards the tiling of detectors into larger arrays [2].
In the case of the HEXITEC system which has pixels on a 250 μm pitch, detectors are flip-chip bonded to the readout ASIC using a gold stud and low-temperature curing silver-loaded epoxy technique. These assemblies are then wire bonded to a PCB module that can be mounted and demounted to the data acquisition system. Using low-temperature curing epoxy allows us to keep CZT crystals at temperatures T <45°C in this bonding process which minimizes adverse effects such as migration of tellurium atoms in the crystal.
For detectors with pixel size far less than 200 x 200 μm^2, the silver epoxy bonding technique is unsuitable due to limitations in the minimum bond size. To allow smaller pitch detectors to be bonded, STFC have recently developed a compression cold-weld indium bump bonding technique. A photolithographic lift-off technique is used to form indium bumps on both the detector and ASIC which are then flip-chip-bonded with the application of <1 g per bond. Results of this new technique for bonding detectors will be presented.

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3D position estimation in monolithic scintillation cameras using B-spline response parametrization.

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Scintillation camera is a position sensitive scintillation detector widely used in medical imaging. The use of monolithic unsegmented crystals was for a long time limited to scintigraphy and SPECT applications, while in PET scanners highly segmented detectors were used. Since recently, the possibility of employing relatively large monolithic scintillators in PET is being also considered. On the other hand, there is a growing interest in replacing the traditionally used center-of-gravity positioning with statistical reconstruction methods such as least squares (LS) or maximum likelihood (ML) which offer, among other advantages, lower distortion near the crystal edges, especially important in the case of compact detectors.
Implementation of statistical event positioning in many cases benefits from parameterization of the photodetector response as a function of coordinates. It was suggested in the literature that using splines for parametrization provides a good compromise between the memory requirements and flexibility. Additional advantages include fast estimation (only arithmetical operations are required) and simple control over regularization.
We developed a library for 2D and 3D B-spline parameterization with the following features:

- fully automatic fit of the spline to 2D and 3D data using cross-validation to optimize the knot number;
- possibility to take into account symmetry of the photosensor response;
- effective dimensionality reduction from 3D to 2D in special cases;

- grouping photosensors with common response function within a group when allowed by the detector geometry.

Here we present our results on B-spline response parametrization (2D and 3D) for several types of the response symmetry. The parametrization technique was successfully applied for 3D positioning performed at graphical processing unit (GPU) hardware using contracting grid search with ML and LS methods with the data obtained through Monte Carlo simulations as well as with those acquired with a scintillation camera. The library is implemented as a part of an open source data processing package ANTS2.

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Characterisation and Modelling of a Thick Segmented Cadmium Tungstate Scintillator Array

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A thick segmented cadmium tungstate scintillator array has been developed at the Rutherford Appleton Laboratory in partnership with the University of Surrey. The array was 1.2 cm x 1.1 cm x 4.4 mm and consisted of 25x24 segments with a 400 μm pitch. This array was created using a novel laser ablation technique. The GATE Monte-Carlo simulation package was used to understand key aspects of its measured performance, in particular the effect of segment pitch and thickness on the mean path length of scintillation photons and the number of reflections that the scintillation photons undergo in the segment. It was found that the mean path length of a scintillation photon was dominated by the optical coupling method which is key in high refractive index scintillators such as cadmium tungstate. The effect of the atomic number and density of the material separating each segment was studied. The higher density, higher atomic number materials had a signal enhancement effect and also reduced amount of cross-talk due to secondary radiation. The measured performance of the prototype array is shown and compared to an ideal array modelled using GATE.

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Development of a Cryogenic Irradiation Test Facility and the Initial Results from a CCD236 Swept Charge Device

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This paper describes the development of a cryogenic irradiation test facility and the initial test of the system to irradiate an e2v technologies CCD236 at -35.4 C with a 10 MeV equivalent proton fluence of 5.0×108 protons.cm-2. The test facility has been developed for the ESA funded study into the radiation damage effects on a p-channel CCD204, and allows for the manipulation of shields and an X-ray fluorescence target to allow the post irradiation characterisation to be

performed at the irradiation facility. The CCD236 is a large area (4.4 cm2) X-ray detector which is readout continually in order to benefit from intrinsic dither mode clocking, suppressing the surface component of dark current. This allows the detector to be operated at warmer temperatures than a conventional CCD, making it an excellent choice to test the facility without the need for extensive time cooling and heating the device under test. The CCD236 will be flown on-board the Chandrayaan-2 and HXMT spacecraft, and the fluence selected is equivalent to 1 year in orbit around the Moon. The analysis on the dark current and energy resolution at Mn-Ka are discussed for data collected pre and post irradiation, and after the device was held at room temperature for a period of 1, 7, 12 and 17 days after the irradiation.
KEYWORDS: Radiation Damage; Cryogenic Irradiation; X-ray detector; SCD

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Gas gain limitation in low pressure proportional counters filled with TEG mixtures

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In the past few years, miniaturized tissue- equivalent gas detectors operating at a nanometric level down to 35 nm, have been developed for application of microdosimetry in radiotherapy. It should be stressed that single ionization events dominate the distribution of low-LET radiation in nanometric sites and therefore their detection is of primary importance. A higher gas gain is necessary for reducing the simulated site. The gas gain factor has been measured for C3H8/CO2/N2/55/39.6/5.4, CH4/CO2/N2/64.4/32.5/3.1 and Ne/C2H4/C2H6/N2/41/39/16.7/3.3 TEG mixtures. The scope of the measurements was to find the highest stable gas gain, its dependence of TEG mixture pressure and counter geometry. Obtained results will be presented.

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X-CSIT: a toolkit for simulating 2D pixel detectors

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A new, modular toolkit for creating simulations of 2D X-ray pixel detectors, X-CSIT (X-ray Camera SImulation Toolkit), is being developed. The toolkit uses three sequential simulations of detector processes including photon interactions, electron charge cloud spreading with a high charge density plasma model and many electronic components used in detector readout. In addition, because of the wide variety in pixel detector design, X-CSIT has been designed as a modular platform so that existing functions can be modified or additional functionality added easily if the specific design of a detector demands it. X-CSIT is under development at UCL for European XFEL, and will be used to create simulations of the three bespoke 2D detectors at European XFEL, AGIPD, LPD and DSSC. These simulations and X-CSIT will be integrated into the European XFEL software framework, Karabo, and through that be available to users to aid with planning of experiments and analysis of data. In addition X-CSIT will be released standalone publicly for other users, collaborations and groups to create simulations of their own detectors.

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Radiation effects on true charge transfer TDI sensor in CMOS

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Time Delay and Integration (TDI) sensors are used to increase Signal to Noise Ratio (SNR) when imaging fast moving objects. Applications include industrial process monitoring and earth observation from aircraft or spacecraft. Radiation hardness needs to be evaluated before operating in the space environment. The subject of this work is a true charge transfer TDI device, manufactured on a CMOS process, intended for earth observation applications. Changes in imaging performance due to irradiation of the TDI sensor are presented. In particular the effect of irradiation on Charge Transfer Efficiency (CTE) is shown.

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Development and Characterization of 16-channel SiPM Prototype with sub-mm pixels for high resolution PET System

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Abstract: SiPMs (Silicon Photomultipliers) are promising photo detectors for high resolution PET system because of its high gain and its fast timing. The resolution of modern PET systems is now in the range of mm. We have newly developed a prototype of 16-channel SiPM with the pitch of 500 µm. One pixel of the developed SiPM consists of 676 APD-geiger mode cells with the size of 15 µm by 15 µm. The cathode of 16-channels SiPM is shared in the die and the anode signals are pulled out in parallel. Each channel is confirmed to be successfully working. The breakdown voltage of the detector is 22.77V and the operational range is from 24 V to 30 V. The absolute PDE calculated from the standard KETEK SiPM is 34% and the peak wavelength is around 420 nm. The measured dark count rate is from 5 to 50 kHz depending on the bias voltage. The basic characteristics of PDE, dark count rate and cross-talk will be presented. The basic performance of 16-channel SiPMs coupled with sub-mm crystal array of Ce:GAGG will be also presented in the conference.

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Low power wireless ultra-wide band transmission of bio signals

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The main objective of this proposal is to design a system for transmission and reception of signals and biological parameters through dedicated radio circuits using a purely digital approach (asynchronous events). Each source of biomedical parameters will be translated into temporal events that can be transmitted and received without further processing. The system, in fact, thanks to its intrinsic use of events, allows controlling in an extremely efficient release of energy for the transmission of information, and therefore exploit an approach completely on-demand to minimize the consumption of power. The events are generated occurrence of particular patterns in the input signal (and then it is extracted the information content of the signal of interest) and efficiently (with respect to energy consumption, complexity, integration and flexibility) synthesized via a digital system asynchronously. The information is transmitted only when required, allowing for a longer battery life than traditional wireless processes. From the technological point of view it will be exploited the wireless transmission techniques that employs the Impulse Radio Ultra-Wide-Band, localized around 3-5 GHz, for transmitting and receiving signals by very reduced temporal pulses, resulting in very wide spectral occupation. As a consequence of that, we gain limited power consumption at the transmitter side. This wireless system can find various applications in the field of medicine, allowing accurate measurements of various biological parameters detected from time to time by a single receiver (collector). The latter will have the task of reworking the received signals to identify the correct sequence and the source of information. The device must have reduced final dimensions to be integrated on a single microchip, which, after having amplified and processed the information of external sensors, must be able to transmit it at distances of the order of meters, possibly using an integrated antenna. The miniaturization of the system to use more sensors, perfectly compatible with low-consumption electronics, can meet the needs of medical applications such as the remote control of biological parameters or the construction of robotic equipment (exoskeletons). The proposed mechanism will be developed in a prototype phase to discrete components in order to validate an initial feasibility study, and will then be integrated microchip in a final stage. We have been able to mount in a preliminary data acquisition chain an amplifier for instrumentation, which we use to interface and read out the bio signals, a voltage controlled oscillator (VCO) to digitize the information and a wireless transmitter.

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Monte Carlo simulation of dose efficiency and image quality in X-ray Luminescence Optical Tomography

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A new hybrid imaging modality, x-ray luminescence optical tomography (XLOT), has been proposed to study problems related to deep-tissue preclinical imaging. In this technique luminescent nanoparticles emit optical photons when irradiated with a collimated x-ray beam. XLOT combines the high sensitivity of optical imaging and the high spatial resolution of x-ray imaging. We are currently building an XLOT prototype using SiPM photodetectors and a low energy x-ray tube. It uses submillimeter diameter collimators to produce an X-ray pencil beam to achieve high spatial localization of the luminescent nanoparticles. The use of this technique for small-animal imaging requires the determination of the dose delivered to the subject. Also, accurate knowledge of the energy deposition map inside the subject is useful for optimization of the optical imaging model used in the tomographic reconstruction. However, the use of a narrow beam of low energy X-rays complicates the use of traditional methods for the determination of the absorbed dose. In this work we report the calculation of the deposited energy distribution map by means of Monte Carlo simulation (PENELOPE v.2011) in the energy range 30-90 kVp. The results show that the dose scales linearly with kVp for a fixed concentration of luminescent nanoparticles and air-kerma rate and that the dose ratio for a 3 mm diameter insert containing 10 mg/ml Gd_2O_2S embedded in a 30 mm diameter water phantom is 6:1. This ratio drops to less than 2:1 for a 1 mg/ml concentration. The imaging performance of the system has been evaluated by means of simulations of the NEMA NU4 image quality and micro-Derenzo phantoms. The results indicate that quantification of the luminescent particle concentration deteriorates with object size, up to 80% when going from 5 to 1 mm diameter objects at 1 mg/ml concentration. The optical spatial resolution using 1 mm step size and 10 degrees angular step is of the order of 1.5 mm.
Acknowledgements. Project PAPIIT IN105913, DGAPA-UNAM, and PAEP-UNAM.

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Feasibility study of a 1 mm resolution small-animal PET prototype

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Our group is developing a one-ring positron emission tomography prototype for small-animals with detector modules consisting of an assembly of 16×16 LYSO scintillation crystals (1×1×10 mm3) coupled to position sensitive photomultiplier tubes (PS-PMT) Hamamatsu H7546B. The detectors are placed in a ring of 9.8 cm inner diameter, with the object under study positioned on a motorized rotating platform. The PS-PMT output signals are reduced with resistive chains and digitized with a multichannel acquisition board based on FPGAs using a coincidence window of 6 ns and 12 bits encoding depth. Sinograms are obtained from list mode data using different rebinning methods (SSRB, MSRB and FORE), while the tomographic images are obtained with analytical (FBP) and iterative algorithms (ML-EM, OSEM) specifically developed for our prototype. The system matrix is calculated using the GATE v6.0 simulation package assuming a realistic geometry of our experimental set-up. Raw data are corrected for spatial distortion, center of rotation, decay and detector non-uniformities (normalization). Energy resolution for individual crystals was obtained with a uniformly distributed cylindrical 18F source, showing a typical value of 21±3%. Sensitivity was obtained using a 22Na source placed at several axial positions covering the whole extent of the scanner. A maximum absolute sensitivity of 0.24% was obtained at the center of the scanner when using 4 detector modules. Spatial resolution was measured using two line sources (0.6 mm inner diameter) and a glass capillary (1.1 mm inner diameter) placed at different radial positions. A resolution of 1.05 mm was obtained using FORE and ML-EM. A tomographic acquisition of a microDerenzo like phantom (one pie section, 1.25 mm diameter hot rods) was obtained and reconstructed with several reconstruction algorithms. All the hot rods were easily resolved, in agreement with the spatial resolution results obtained with the line sources

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The Effect of radiation on the spatial resolution of a novel proton range detector for use in proton Computed Tomography

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Dr Tony Price, Prof Stuart Green, Dr Spyros Manolopoulos, Prof David Parker on behalf of the PRaVDA Consortium
The recent expansion in particle based radiotherapy worldwide is coupled with an increased demand for research in the area to improve cancer treatments. The goal of the Proton Radiotherapy Verification and Dosimetry Applications (PRaVDA) Consortium is to develop a solid state device with the capability of monitoring the particle beam during patient treatment together with a capability to perform proton Computed Tomography (pCT) scans of the patient.
In order to acquire a pCT scan the residual energy of each individual proton must be measured. PRaVDA have designed a device which uses large scale CMOS sensors to track the protons and measure their range after the patient. Previous attempts at measuring the residual range of the protons using scintillators have been hampered by the requirement to have a low proton current

in the device. The technology choice for the PRaVDA device means it will be able to acquire data at an increased proton beam current.
The maximum possible proton current is set by the devices ability to distinguish between individual protons. The device's performance is expected to degrade with radiation damage. Hence there is a requirement for large area pixelated CMOS detectors which are resistant to radiation damage. The THORe sensor is a test CMOS chip with various radiation resistant architectures. Here we will present results on its performance following irradiations at different dose levels with 36 MeV protons from the Scanditronix MC40 cyclotron at the University of Birmingham. The device ageing with increasing levels of radiation damage will be evaluated by measuring the modulation transfer function (MTF), noise power spectrum (NPS), and signal to noise ratio measurements. The result of the THORe sensor irradiations will influence the design of PRAVDA's CMOS sensor. Moreover, because THORe contains a similar architecture to the one envisaged for PRAVDA's sensor, it will be possible to estimate the maximum beam current that could be detected in the PRaVDA range telescope before the onset of track ambiguities and similar issues that could affect the device's performance at high rates and thus impact on the quality of the pCT scan.

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Radiation-induced charge trapping in n- and p-channel CCDs

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Recent developments in pocket pumping techniques have enabled the study of charge-trapping defects in both n-channel and p-channel CCDs. These techniques allow for analysis of individual defects, which can be located in the device to within a few microns.
The ability of pocket pumping to analyse individual traps coupled with the large number of defects present within the silicon lattice after irradiation allows for determination of the trap properties, such as the emission time constants, of single defects for each of the main trap species, giving a much greater degree of accuracy than is available with methods which analyse bulk trap properties such as deep level transient spectroscopy (DLTS).
Pocket pumping and related techniques can be used on both n-channel and p-channel devices, permitting the study of both electron and hole traps in silicon across the entire band gap. Furthermore, the ability to study defects in situ and with precise localisation allows for different charge states of defects to be studied where they exist, for example in the case of the negative and doubly negative charge states of the divacancy as an electron trap.
In this study we have encountered many examples of defects within both types of device. Whilst many of these charge traps behave as one might expect, the most interesting points of this research are those which have certain peculiarities. Here we present the latest results across a range of devices, with particular interest paid to how the defects interact with signal charge as it is transferred through the device.

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The Belle II DEPFET Pixel Detector and Cluster Shape Dependent Improvement of Spatial Resolution

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On behalf of the DEPFET Collaboration

The high energy experiment Belle II - an upgrade of the previous successful Belle experiment in the KEK Japanese flavor factory - is under construction. Belle II will be built on a new electron-positron machine (SuperKEKB) designed to deliver instantaneous luminosity 40 times higher than the world record set by its predecessor KEKB, and 50 ab-1 in a decade of operation. Commissioning and first physics runs are expected in 2016.
Belle II will be equipped with a new pixel vertex detector (PXD), based on the DEPFET (DEPleted Field Effect Transistor) technology, which is now under construction. The detector is located extremely close to the interaction point and consists of two layers of DEPFET active pixel sensors, in total of 8 million channels. Production of sensors and other components (chips, readout electronics, mechanics, cooling...) is in time for installation in summer 2016.
The DEPFET technology combines detection in fully depleted silicon bulk with in-pixel amplification by a field effect transistor integrated in every pixel. Belle II will use DEPFET sensors thinned down to 75 microns, with low power consumption and low intrinsic noise.
Constraints on material budget, data rates, and signal-to-noise required several design decisions in the pixel layers. The rolling-shutter readout minimizes dead time, and a special "gated mode" feature allows to "freeze" data acquisition during periods of high beam background noise. To achieve feasible data rates, there are several levels of data reduction: pixel sizes vary by sensor region, and only data from regions of interest (ROIs) identified by silicon-only tracking (that is, using 4 layers of the Belle II strip vertex detector) or full tracking are stored.
The functionality of the chosen concept was confirmed in a beam test at DESY in January 2014, with pixel and strip sensors, pixel telescopes and magnetic field.
The simulation, data acquisition and analysis paths of the Belle II software framework (basf2) were successfully used for real DEPFET and strip detector data streams with ROI selection algorithms. A detailed study of pixel clusters in zero suppression mode found systematic effects of cluster shape on reconstructed position and spatial resolution. The observations on beam test data are confirmed with simulations and a general scheme of cluster-shape dependent response correction will be presented.

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Novel Silicon Drift Detector Design Enabling Low Dark Noise and Simple Manufacturing

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The Silicon Drift Detectors (SDDs) have replaced simple diodes in demanding X-ray fluorescence applications like in element analyzers capable of detecting light elements. The reason for this is that with similar collection area the SDD's have a much smaller output capacitance due to a much smaller anode size and thus much better Signal to Noise Ratio (SNR) at small signal levels than diodes. This is achieved by placing around a miniature sized anode rings that are biased such that inside the SDD's fully depleted bulk a horizontal electric field component is established guiding signal charges towards the anode. A typical problem still present in SDDs is interface generated dark noise, which is caused when leakage current generated at depleted interfaces mixes with the signal charge.
It has been shown previously that it is possible to prevent the formation of interface generated dark noise in SDDs, for example by implementing at SDD's interface "electron rivers" as demonstrated by W. Chen at al. But the realization of such SDDs has been rather complicated.
We present an advanced SDD design comprising a novel ring arrangement preventing the formation of interface generated dark noise and enabling simple manufacturing with standard process steps. In this work the design and operation principle of the proposed SDD are presented.
The operation of the proposed SDD has been evaluated on TCAD with 2D process and device simulations. The simulation results demonstrate the viability of the design and the operation principle of the proposed novel SDD design as well as the absence of interface generated dark noise.

Key words: silicon drift detector, SDD, device simulation, interface generated dark noise, interface leakage current.

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Position sensitive detector for fluorescence lifetime imaging.

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We present a detector system with a microchannel plate based photomultiplier tube and its application for fluorescence lifetime imaging (FLIM). A capacity coupled imaging technique (charge image) combined with a charge division anode is employed for the positional readout. Using an artificial neural networks computation model we are able to reconstruct the position of the incident photon as precise as 20 microns over the detector active area of 25 mm diameter. Thus, the resulting image quality corresponds roughly to a megapixel conventional CCD camera. Importantly, it is feasible to reach such resolution using only 9 charge acquisition channels supporting the anode structure of 14 interconnected readout electrodes. Additionally, the system features better than 50 ps temporal resolution allowing single photon counting FLIM acquisition with a regular fluorescence wide-field microscope.

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Development of a Prototype PET Scanner using Dual-Sided Readout DOI-PET Modules

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In conventional PET scanners, spatial resolution deteriorates near the edges of the field of view due to the uncertain depth of interaction (DOI) within thick detectors. In our previous study, we reported the novel design of a gamma-ray detector that can measure DOI information. This detector was based on a segmented 3-D scintillator array composed of $0.8 \times 0.8 \times 5$-mm^3 Ce-doped $Gd_3Al_2Ga_3O_{12}$ (Ce:GAGG) crystals and two large-area monolithic Multi-Pixel Photon Counter (MPPC) arrays coupled to both ends of the scintillator array. Moreover, the detector showed good energy resolution of 11.8% and clear separation of each crystal at energy of 662keV. In this research, we developed a one-pair coincidence system using 3-D scintillator arrays composed of $1 \times 1 \times 3$-mm^3 Ce:GAGG crystals to simulate a PET gantry, and evaluated the influence of DOI information on spatial resolution.

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A Novel Compton Camera Design featuring a Rear-panel Shield for Substantial Noise Reduction in Gamma-ray Images

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After the Japanese nuclear disaster in 2011, large amounts of radioactive isotopes were released and still remain a serious problem in Japan. Consequently, various gamma cameras are being developed to help identify radiation hotspots and ensure effective decontamination operation. The Compton camera utilizes the kinematics of Compton scattering to contract a source image without using a mechanical collimator, and features a wide field of view. For instance, we have developed a novel Compton camera that features a small size (13 x 14 x 15 cm^3) and light weight (1.9 kg), but which also achieves high sensitivity thanks to Ce:GAGG scintillators optically coupled with MPPC arrays. By definition, in such a Compton camera, gamma rays are expected to scatter in the "scatterer" and then be fully absorbed in the "absorber" (in what is called a forward-scattered event). However, high energy gamma rays often interact with the detector in the opposite direction—initially scattered in the absorber and then absorbed in the scatterer—in what is called a "back-scattered" event. Any contamination of such back-scattered events is known to substantially degrade the quality of gamma-ray images, but determining the order of gamma-ray interaction based solely on energy deposits in the scatterer and absorber is quite difficult. For this reason, we propose a novel yet simple Compton camera design that includes a rear-panel shield (a few mm thick) consisting of W and/or Sn, located just behind the scatterer. Since the energy of scattered gamma rays in back-scattered events is much lower than that in forward-scattered events, we can effectively discriminate and reduce back-scattered events to improve the signal-to-noise ratio in the images. This paper presents our detailed optimization of the rear-panel shield using Geant-4 simulation, and describes a demonstration test using our Compton camera.

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One dimensional x-ray detector with high spectroscopic performance based on silicon strip detector technology

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Over the last decade silicon strip detectors have become a standard in X-ray diffraction instrumentation. The primary advantage of these detectors is high measurement speed and high count rate capability achieved by fully parallel readout of multi-strip sensors. In our previous work 1 we have demonstrated that using a standard silicon strip detector technology combined with high performance front-end electronics one can build a device with energy resolution of 600 eV FWHM at room temperature. This energy resolution is sufficient to address a common problem in X-ray powder diffraction in particular, i.e. electronic suppressing the Fe fluorescence radiation from samples containing iron or cobalt while irradiated with 8.05 keV photons from an X-ray tube with the Cu anode.
Further improvement of the energy resolution of such detectors is highly desirable to enable electronic discrimination between the Kα and Kβ emission lines when using an X-ray tube. This will allow eliminating the monochromators on the primary or diffracted beam, which cause significant reduction of the beam intensity. For the commonly used Cu anode the Kα and Kβ are 8.05 keV and 8.9 keV respectively and the energy resolution better than 400 eV FWHM (corresponding to Equivalent Noise Charge of 46 el. rms) is required to suppress the Kβ line efficiently.
In the paper a new detector design that achieving a global energy resolution for the entire detector of about 350 eV FWHM at room temperature is presented. The measured global energy resolution is defined by the energy spectra summed over all strips of the detector, and thus includes charge

sharing effects, electronic noise of the front-end electronics, matching of parameters across the channels and other system noise sources. The target energy resolution has been achieved by segmentation of the strips to reduce their capacitance and by careful optimisation of the front-end electronics. Excellent noise and matching performance and negligible system noise allow us to operate the detector with a discrimination threshold as low as 1 keV and to measure fluorescence radiation lines of light elements, down to Al Kα of 1.5 keV, simultaneously with measurements of the diffraction patterns.
Critical design aspects of the detector will be discussed and test results illustrating the detector performance will be presented in the paper.
1 W. Dąbrowski, et al., Journal of Instrumentation, 7 (2012) P03002

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Influence of edge surface leakage current on the performance of pixelated CdTe radiation detectors

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Small pixel CdTe radiation detectors provide excellent spatial and energy resolution for spectroscopic X-ray imaging. The high leakage current of CdTe, originated by its bulk and lateral edges, limits the performance of CdTe at high bias potentials. Guard bands are used to prevent interference of edge leakage current with the radiation signal. In the production of large flat panel CdTe radiation detectors through the tiling of CdTe modules, guard bands need to be minimised or removed to increase the active detection area. This paper will characterise the edge leakage current and its consequences on spectroscopy acquired with small pixel CdTe detectors in order to build successful large flat panel CdTe detectors.
The contribution of edge leakage current has been separated from the total leakage current. Its dependence on time, temperature and bias will be investigated. Measurements will be presented for twenty Schottky CdTe detectors with a pixel pitch of 250 μm. In these detectors it has been found that the edge leakage current density is consistently higher than the bulk leakage current density and is responsible for the detector breakdown at high voltages.
The cause of high edge leakage current and its localised character will be presented and the effects of high leakage currents on small pixel spectroscopy discussed.

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Development of a MPPC-based Prototype Gantry for Future MRI-PET Scanners

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We have developed a high spatial resolution, compact Positron Emission Tomography (PET) module designed for small animals and intended for use in magnetic resonance imaging (MRI) systems. This module consists of large-area, 4 × 4 ch MPPC arrays (S11827-3344MF; Hamamatsu Photonics K.K.) optically coupled with Ce-doped $(Lu,Y)_2(SiO_4)O$ (Ce:LYSO) scintillators fabricated into 15 × 15 matrices of 0.5 × 0.5 mm^2 pixels. We set the temperature sensor (LM73CIMK-0; National Semiconductor Corp.) at the rear of the MPPC acceptance surface, and apply optimum voltage to maintain the gain. The eight MPPC-based PET modules and coincidence circuits were assembled into a gantry arranged in a ring 90 mm in diameter to form the MPPC-based PET system. We have developed two types PET gantry: one made of non-magnetic metal and the other made of acrylonitrile butadiene styrene (ABS) resins. The PET gantry was positioned around the RF coil of the 4.7 T MRI system. We took an image of a point ^{22}Na source under fast spin echo (FSE) and gradient echo (GE), in order to measure the interference between the MPPC-based PET and MRI. The spatial resolution of PET imaging in a transaxial plane of 1 mm or less (FWHM) was achieved in all cases. Operating with PET made of ABS has no effect on MR images, while operating with PET made of non-magnetic metal has a significant detrimental effect on MR images. This paper describes our quantitative evaluations of PET images and MR images, and presents a more advanced version of the gantry for future MRI/DOI-PET systems.

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Setup for Laboratory studies of the charge transport in Silicon Dioxide

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The position sensitive detectors operate in high intensity radiation field of the collider experiment 1. Important task is to estimate the influence of different radiation effects on properties of the detector. We focus on the laboratory studies to estimate a reliability of different types of silicon detectors. We use the simple test structures produced by standard technology for the silicon detectors. We give the primary attention to the case when the depth of active detector region varies from 10 to 20um because it leads to the most significant influence of SiO2-Si interface on a processes in silicon bulk. We present the experimental results of long term irradiation test with Am241 (one year) of the slow charge transport inside the SiO2-pSi-iSi-nSiSiO2 structures. Some theoretical calculations are presented for MAPS, APS and position sensitive detectors with large active area - SSD, SDD.
References: 1 Thomas Peitzmann (for the ALICE Collaboration), Journal of Physics G: Nuclear and Particle Physics, Vol. 38, No 17, (2011).

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Microdosimetric response of proportional counters filled with different tissue-equivalent gases.

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In pulse mode operation each detector at the output gives pulse hight spectra. These pulse hight spectra from tissue-equivalent proportional counters are recalculated to microdosimetric quantity like y*f(y)*, *y*d(y) or y*h60(y) or others, for expressing the radiation quality. The pulse – hight spectra from different in geometry, proportional counters have been measured for three different TEG mixtures (C3H8/CO2/N2, CH4/CO2/N2 and Ne/C2H4/C2H6/N2). The measurements have been made for the same counters, in the same geometry and radiation fields, only mixtures were different. All obtained spectra were normalised to permit their direct comparison. The

mixtures pressures were varied in the range from 12 hPa to 300 hPa to have simulated tissue target diameter of the order of a few µm, from 0,4 µm to 8 µm.. It was found out that the microdosimetric distributions are similar but some differences are observed up to 10%. The dose – mean energy for all spectra was determined and employed for expressing the average radiation quality. Detailes will be presented.

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Electrical-modeling and simulation of cumulative radiation effects in semiconductor pixels detectors: prospects and limits

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Silicon detectors have gained in popularity since silicon became one of widely used micro/nanolectronic semiconductor material. In particle physics as well as for room radiation detection or imaging , silicon is now a common feature for pixel based detecting systems. Over the past twenty years a lot of experimental efforts have been focused on the effects of ionizing and non-ionizing radiation on silicon pixels. Most of this research was done in the framework of high luminosity particle physics experiments, along with radiation hardness studies in basic semiconductors devices. In its simplest form the Si detectors reduce to a PIN or PN structure partially or totally depleted, or in some other cases MOS structures. Bulk or surface defects affect considerably the transport of free carriers and therefore some modeling of the effects of deep defects can be done in a conservative way, using existing or experimentally obtained data. The proposed method to design a pixel detector is based on the use the electrical properties of points or extended defects either at the interfaces or in the bulk. Their electrical and physical properties are introduced in a standard code in order to make predictive simulations. The proposed procedure can be used to study pixels detectors with different geometrical structures and alternative semiconducting materials. Its purpose is to provide an alternative to tedious and extensive radiation tests.This could allow the development of defect annealing methods, which are necessary for the long term realiability of detectors. In this paper we will describe a general method for pixel design and we will show how it can be used on silicon and germanium pixels.

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Performance tests during the IBL Stave Integration

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In preparation of the ATLAS Pixel Insertable B-Layer integration, detector components, so called staves, were mounted around the Beryllium ATLAS beam pipe and tested using production quality assurance measurements as well as dedicated data taking runs to validate a correct grounding and shielding schema. Each stave consists of 32 FE-I4 readout chips of ~ 2x2cm size which sums up to over 860k pixels per stave. The integration tests include verification that neither the silicon n-in-n nor the silicon 3D sensors were damaged by mechanical stress, and that their readout chips, including their bump bond and wire bond connections, did not suffered from the integration process. Evolution of the IBL performance during its integration will be discussed as well as its final performance before installation.

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3D simulation and measurements of novel bias grid and

edgeless ATLAS planar pixel sensor designs for the High-Luminosity LHC upgrade

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Substantial upgrades to the ATLAS Inner Detector (ID) must occur in order to be capable of withstanding the increase in occupancy and radiation damage expected from an upgrade to the High-Luminosity Large Hadron Collider (HL-LHC) in 2022. Minimisation of inactive regions for pixel detectors in ATLAS can be achieved through active edge design, where as implementation of alternative bias rail geometries can decrease efficiency loss. These improvements are desired to allow devices to be placed adjacently (instead of shingled), reducing cooling requirements, power consumption and material budget. Thinning of sensors increases radiation hardness, a vital parameter in the selection of pixel technologies for the inner layers which will be exposed to high particle fluence.
In this presentation three-dimensional simulations with Technology Computer Aided Design (TCAD), required to develop and optimise processing techniques for novel designs such as thin and edgeless structures, will be shown. Characterisation in a laboratory environment has been performed to study sensors coupled to ATLAS FE-I4 readout chips. Measurements include IV curves, laser scans, and source scans with radioactive sources and cosmic muons. Charge collection measurements for non-perpendicular particle tracks, resulting in charge clusters, have also been performed. Selected devices will be irradiated to analyse the performance of sensor designs at fluences expected in the ATLAS ID for the HL-LHC. Furthermore, comparison of simulation with Secondary Ion Mass Spectrometry (SIMS) measurements to study the doping profile of structures will be included.

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The CMS Pixel Readout Chip for the Phase I Upgrade

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The CMS silicon pixel detector is the innermost component of the all-silicon tracking system of CMS. While the current pixel detector is designed for and performing well at the current LHC luminosity, it would be subject to severe inefficiencies at increased hit occupancy of the detector. Based on the strong performance of the LHC accelerator, it is anticipated that peak luminosities of two times the design luminosity of $\mathcal{L} = 2 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ are likely to be reached before 2018 and perhaps significantly exceeded in the running period until 2022, referred to as Phase I.
Therefore, an upgrade of the CMS pixel detector is planned, including a new readout chip, additional barrel detector layer and end-cap disks for robust tracking performance, and a significantly reduced overall material budget. The new readout chip design comprises additional on-chip buffer cells as well as a high-speed data link and a low-threshold comparator in the pixel cells. With these changes the upgraded pixel detector will be able to sustain the efficiency of the current pixel tracker at the increased requirements imposed by high luminosities and pile-up.
The effects of these design changes on e.g. position resolution and charge collection efficiency have been studied in detail using a precision tracking telescope at the DESY electron test beam facilities. The telescope track resolution of down to 4 ¯m enables precise studies of tracking efficiency, charge sharing and collection even within single pixel cells of the device under test.
The new CMS pixel detector modules have been found to perform well. The lower pixel-cell charge threshold of about $\sim$ 1.5k electrons allows for a reduced spatial resolution of $\sim$ 6 ¯m. Detailed simulations of sensor charge collection and chip thresholds have been conducted in order to verify the results and show good agreement with the test beam data. Furthermore, chip prototypes

have been irradiated up to the anticipated lifetime dose of the CMS pixel detector outer layer of 130 kGy and were measured to be still $\sim 99.8\,\%$ efficient.
This contribution focuses on the improved performance and capabilities of the new pixel readout chip and summarizes results from test beam campaigns and additional measurements conducted in order to assure the functionality of the new chip design with its improved charge threshold, redesigned data transmission and buffering scheme.

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Enhancing gamma-ray detection and imaging characteristics in HPGe double-sides strip detectors employing signal decomposition algorithms

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Position sensitive semiconductors are important tools for gamma-ray detection and imaging. Compton Imaging is now an established gamma ray imaging modality for energies ranging from about 200 keV to several MeV. The performance is only limited by intrinsic detector properties such as position and energy resolution and the ability to resolve individual interactions. In our effort we focus on the improvement of the position resolution of HPGe double-sided strip detectors (DSSD). Our detectors are 15 mm thick and have 38 strips on each side with a strip pitch of 2 mm resulting in a volume of about 100 cm3 that is read out by 76 individual preamplifiers. We are developing and benchmarking signal processing techniques to improve the position resolution to be significantly better than given by the voxel size. Specifically, we are developing Signal Decomposition (SD) algorithms, which are based on physic models of the charge creation and transport processes and mathematical techniques such as singular value decomposition to infer the energy and three-dimension of individual gamma-ray interactions. Using SD we were able to achieve a spatial resolution of about 0.5 mm resulting in about 800k spatial voxels. The increase in granularity significantly increases the imaging resolution and efficiency, which is the ultimate goal.

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3D Monolithically Stacked CMOS Active Pixel Sensors for Particle Position and Direction Measurements

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Particle tracking systems for trajectory reconstruction in High Energy Physics experiments are usually based on different separated sensing layers, featuring pixels and/or strips elements. In this work we propose a 3D monolithically stacked, multi-layer detectors based on CMOS Active Pixel Sensors (APS) layers which allows at the same time accurate estimation of the impact point and of the incidence angle an ionizing particle. The whole system features two fully-functional CMOS APS matrix detectors, including both sensing area and control/signal elaboration circuitry, stacked in a monolithic device by means of Through Silicon Via (TSV) connections thanks to the capabilities of the CMOS vertical scale integration (3D-IC) 130nm Chartered/Tezzaron technology.

In particular, we present the results of the characterization of different chip prototypes, that have been extensively tested in laboratory using a variety of ionizing radiation sources (laser, X-rays). However, in order to evaluate the suitability of the two layer monolithic active pixel sensor system to reconstruct particle tracks, tests with proton beams have been carried out at the INFN LABEC laboratories in Florence (Italy).
Particle direction and angle measurements have been carried out by parallel reading of the corresponding outer and inner pixel matrices fostering particle momentum evaluation within a single, multiple layers, 3D vertically stacked APS CMOS detector. It should be noticed as well that this approach could significantly reduce the problems of the material budget and multiple scattering of tracking systems, since the top layer has been thinned down to about ten micrometres, and the distance between the two layers is of the same order of magnitude.

https://www.dropbox.com/s/rp6telp0x3dig0j/passeri_PSD_i

Figure 1: Fig. 1: The test set-up at INFN LABEC Labs. Florence (Italy).

https://www.dropbox.com/s/bnz3ijawo1eky7b/passeri_PSD_i

Figure 2: Fig. 2: Coordinate residual measurements as a function of the particle incidence angle.

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PImMS2, a CMOS event-triggered time-stamping image sensor with storage of multiple timestamps

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PImMS, or Pixel Imaging Mass Spectrometry, is a family of high-speed monolithic CMOS imaging sensors tailored to the requirements of mass spectrometry and related fields. PImMS pixels each compare step events of collected charge to an adjustable threshold, storing up to four significant events inside the pixel as 12-bit timestamps with time bin durations down to 12.5ns (80MHz). The pixels may be individually trimmed to improve the uniformity of response. The pixels measure 70μm by 70μm and each contain over 600 transistors. PImMS2 is the second generation of these sensors, providing a larger sensor area with 324 by 324 pixels and new features. We will present an overview of the pixel and sensor architecture, recent characterisation results for PImMS2 and application results for PImMS1 and PImMS2.

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Radiation-hard Active Pixel Sensors for HL-LHC Detector Upgrades based on HV/HR-CMOS Technology

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We explore the concept of using deep-submicron HV-CMOS and imaging processes to produce a replacement for traditional radiation-hard silicon sensors. Unlike fully integrated monolithic active pixel sensors (MAPS), such active sensors contain simple circuits, e.g. amplifiers and discriminators, but still require a readout chip - which can be a traditional strip or pixel readout chip or a tailor-made one without any analogue circuits. This approach yields most of the advantages of MAPS (improved resolution, reduced cost and material budget, etc.), without the complication of full integration on a single chip; in particular, high-speed clocked circuits necessary for trigger handling and efficient communication can be kept separated from the crosstalk-susceptible pre-amplifiers.
The design of test ASICs produced in different processes, characterization results before and after irradiation and experience obtained with pixel and strip readout will be shown. In addition, plans for further submissions with higher-resistivity substrates will be outlined and an outlook will be given on application options for HL-LHC detector upgrades.

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Large area CdTe based spectroscopic X-ray imaging detector

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A 100mm x 100mm area X-ray detector has been built by tiling 25 modules of CdTe detectors. Each module consists of a 1mm thick CdTe detector bump bonded to an 80x80 pixel readout ASIC. Previous publications have demonstrated the use of similar single module or 4-module systems for applications such as X-ray diffraction or small area SPECT imaging. Tiling the 25 modules to create this larger array has created several technical challenges. In this paper we describe the latest X-ray imaging and spectroscopic performance of the modules and the design considerations and solutions for constructing the large array. Specifically we have achieved accurately aligned mechanics to minimise the dead areas when using the 3-side buttable modules. At the same time we have to remove heat from the array and allow high bandwidth data connection to the modules. The detector has a multi-level processing system which digitises 2x109 analogue signals per

second. Each data value can represent the energy of the X-ray photon digitised to 12-bit accuracy. This raw data can be locally processed or stored and streamed off the detector for subsequent processing. This detector has 400 x 400 pixels with better than 2keV FWHM resolution giving it a capability for many disruptive applications.

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A Radiation Detector Design Mitigating Problems Related to Sawed Edges

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In pixelated silicon radiation detectors that are utilized for the detection of UV, visible, and Near Infra-Red (NIR) light it is desirable to utilize a relatively thick fully depleted Back-Side Illuminated (BSI) detector design. The benefit of the BSI configuration is that structures on the front side like metal wirings do not stand in the way of light enabling thus 100 % Fill Factor (FF). The advantages of the fully depleted configuration are considerably reduced Cross-Talk (CT) due to lack of diffusion and improved Quantum Efficiency (QE) due to lack of recombination.
Thicker fully depleted detectors have better QE for NIR light but the disadvantages are that more dark current is generated in the depleted bulk (which can be, however, mitigated by cooling), that a bigger bias is required at a conductive backside layer in order to fully deplete the bulk, and that the CT is larger, especially at the boundary of the pixel matrix. Thus there is an optimal detector thickness depending mainly on the optics, the magnitude of the bias on the conductive backside layer, and the pixel size.
In case thinner than 300 um thick detectors are required it is more or less mandatory to thin the detector wafer from the backside after the front side of the detector has been processed and before the conductive layer is formed on the backside. One option is to bond the front side of the detector wafer to a support wafer. The problem is, however, that it is not trivial to reach the contact pads located on the front side of the detector wafer especially if the detector is thicker than 40 um. This problem can be avoided in TAIKO thinning process since no support wafer is required but the detector thickness must be at least 40 um. The TAIKO process has, however, the problem that lithographic steps cannot be performed on the backside of the detector wafer. This means that the conductive backside layer must be homogenous throughout the wafer and that the contact to the conducting backside layer should be placed on the front side of the detector.
In order to provide good QE for blue and UV light the conductive backside layer should be as thin as possible and it should be of opposite doping type than the substrate (an inversion layer is not an option due to the relatively thick fully depleted substrate). Beside the use of TAIKO process it is hereby assumed that the detector chips are separated from the wafer by sawing which is a standard procedure in chip manufacturing. The problem with afore described arrangement is that it is difficult to bias the conductive backside layer from the front side. Another typical problem is that a lot of leakage current is generated at the sawed chip edge, which increases the power consumption.
In this paper a sawed TAIKO detector chip arrangement is presented comprising fully depleted BSI configuration, thickness between 40 and 300 um, low power consumption, as well as good QE for UV, visible, and NIR light.
Key words: detector chip design, process simulation, device simulation, fully depleted, back-side illuminated, high quantum efficiency, low crosstalk, low power consumption.

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Experimental results for the Cherwell MAPS sensors

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We report on the status and performance of the CMOS Monolithic Active Pixel Sensor (MAPS) Cherwell 1, 2 and 3 sensors for the detection of charged particles in vertexing, tracking, and calorimetry applications. Cherwell is a 4-T CMOS sensor in 180 nm technology on a 12um epitaxial substrate with low-noise, low-power, in-pixel correlated double sampling, and high conversion gain.
Cherwell 1 was developed for Linear Collider studies and consists of four arrays, two optimized for vertexing and tracking applications, and two for digital calorimetry applications. The vertexing arrangements have a matrix of 96x48 pixels with a pitch of 25 um. The "reference array" is readout on a rolling shutter base with a fine resolution 12-bit, single-slope column parallel ADC. The "strixel" array has the readout and ADC circuits embedded in the space between the pixel diodes. The two sections for calorimetry have a matrix of 96x48 pixels with 25 um pitch and 48x24 pixels with 50 um pitch, respectively. Additional circuitry is added to provide charge summing of 2x2 pixels during readout.
Cherwell 2 and 3 are prototype candidate sensors developed for the upgrade of the ALICE Inner Tracker System at the LHC. A number of variants have been produced on an 128x128 pixel array with a 20um pitch using the strixel technology.
We report on the characterisation and performance of the prototypes, on the test bench, and at the test beam.

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(Invited) Position Sensitive Detectors in Security Imaging

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Both one-dimensional and two-dimensional position sensitive detectors are deployed widely for creating X-ray images in the security inspection industry. The majority of these sensors are based on scintillation detectors with photodiode readout. However, the constraints in image quality, allowable dose to the object, the need for quantitative inspection and control over manufactured cost lead to a careful optimization of detector design for every application. The design of position sensitive detectors for low energy X-ray (< 300 keV), high energy X-ray (> 1 MeV) and Compton scatter based X-ray imaging systems are reviewed and example detector configuration and associated images are presented.

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Imaging of Ra-223 with a small-pixel CdTe detector: potential for improved image quantification for radionuclide dosimetry

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Ra-223 Dichloride (Xofigo™) is a promising new radiopharmaceutical offering survival benefit and palliation of painful bone metastases in patients with hormone-refractory prostate cancer 1. The response to radionuclide therapy and toxicity are directly linked to the absorbed radiation doses to the tumour and organs at risk respectively. Accurate dosimetry necessitates quantitative imaging of the biodistribution and kinetics of the radiopharmaceutical. Although primarily an alpha-emitter, Ra-223 also has some low-abundance x-ray and gamma emissions, which enable imaging of the biodistribution in the patient. However, the low spectral resolution of conventional gamma camera detectors makes in-vivo imaging of Ra-223 challenging. In this work, we present spectra and image data of anthropomorphic phantoms containing Ra-223 acquired with a small-pixel CdTe detector (HEXITEC) 1 with a pinhole collimator. Comparison is made with similar data acquired using a clinical gamma camera. The results demonstrate the advantages of the solid state detector in terms of scatter rejection and quantitative accuracy of the images. However, optimised collimation is needed in order for the sensitivity to rival current clinical systems.
As different dosage levels and administration regimens for this drug are explored in current clinical trials, there is a clear need to develop improved imaging technologies that will enable personalised treatments to be designed for patients.
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2 P Seller et al. *Pixellated Cd(Zn)Te instrument*, JInst, 2011, C12009

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A Small Field of View Camera for Hybrid Gamma and Optical Imaging

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The development of compact low profile detectors has allowed the production of small field of view, hand held imaging devices for use at the patient bedside and in operating theatres. The combination of an optical and a gamma-ray camera, in a co-aligned configuration, offers high spatial resolution multi-modality imaging giving a superimposed scintigraphic and optical image. This innovative introduction of hybrid imaging offers new possibilities for assisting surgeons in localizing the site of uptake in procedures such as sentinel node detection.
Materials and Methods: We have developed a compact hybrid gamma-optical camera of weight approximately 1kg, consisting of a 600 µm thick CsI(Tl) columnar scintillator coupled to an electron multiplying CCD. A tungsten collimator with a 0.5mm diameter pinhole produces a 40x40mm nominal field of view (FOV) and alignment with an optical camera provides the same FOV as the gamma camera for image superimposition. Images are recorded simultaneously and presented in a fused co-aligned display of the two modalities. Performance characteristics

including sensitivity, spatial resolution and count rate response, have been measured based on protocols adapted for use with high-resolution small FOV systems.
Results: The characteristics of the hybrid camera compared favourably with other portable gamma cameras currently available. Spatial resolution <1mm was recorded with system sensitivity of up to 214cps/MBq. A simulated node 2mm in diameter containing 2MBq 99mTc was detectable (signal-to-noise ratio 25) situated 10mm from a simulated injection site 8mm in diameter with an activity of 32MBq at a source-to-camera distance of 55mm. The new hybrid system is being clinically evaluated and initial results from imaging patient volunteers are very encouraging.
Conclusion: The anatomical context provided by the optical camera aids the physical localisation of radiopharmaceutical uptake in patients. The compact size and fused display makes the system ideal for surgical use, where optical information can aid localisation of sites of uptake, such as in sentinel node detection. Initial patient images show the utility of the system and encourages us to carry out further evaluation in the surgical theatre setting.

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Operational performance characteristics of the WISH detector array on the ISIS spallation neutron source

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The performance of the position sensitive neutron detector array of the WISH diffractometer is discussed. WISH (Wide angle In a Single Histogram) is one of the seven instruments currently available for users on the second target station (TS2) of the ISIS spallation neutron source, and is used mainly for magnetic studies of materials. WISH is instrumented with an array of 10 detector panels, covering an angular range of 320 degrees, orientated in two semi-cylindrical annuli around a central sample position at a radius of 2.2m. In total the 10 detector panels are composed of 1520 3He based position sensitive detector tubes. Each tube has an active length of one metre, a diameter of 8 mm and is filled with 3He at 15 bars.
The specification for the WISH detectors included a neutron detector efficiency of 50% at a wavelength of 1Å, good gamma rejection and a position resolution better than 8 mm FWHM along the length of the tubes all of which have been met experimentally. Results obtained from the detector arrays showing pulse height and positional information both prior to and post installation will be shown. The first 5 of the 10 detector panels have been operational since 2008, and comparable diffraction data from powder and single crystal samples taken from the remaining 5 panels (installation completed in 2013) shows that we have a highly stable detector array which is easily assembled and maintained.
Finally some real user data will be shown, the quality of which has enabled WISH to become one of ISIS' flagship instruments, providing by far the largest data volume of any of the ISIS TS2 instruments to date.

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New Detection System for Heavy Element Research

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New detection system design for heavy element research with 48Ca projectile has been reported. This system is based on application of 32 position sensitive strip PIPS detector and low pressure pentane filled TOF detector application in 48Ca induced nuclear reactions. To suppress beam associated background products new version of real-time method of "active correlations" has been applied. Examples of applications in 249Bk+48Ca and 243Am+48Ca reactions are presented. The system development to operate together (in parallel) with the digital ORNL (TN,US) detection system to provide a quick search for ER-alpha correlation chains has been discussed too. In that case the system operates with DSSSD large area Micron Semiconductors detector.

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Position sensitive photon detectors using epitaxial InGaAs/InAlAs quantum-well

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This work deals with investigation of novel position sensitive devices based on InGaAs/InAlAs Quantum Well (QW) for several applications of either synchrotron or conventional light sources. Such QW devices may be used as fast and efficient detectors due to the direct, low-energy band gap and high electron mobility at Room Temperature (RT).
Metamorphic In0.75Ga0.25As/ In0.75Al0.25As QWs containing a two-dimensional electron gas (2DEG) were grown by Molecular Beam Epitaxy (MBE). The carrier mobility at RT was 1.2×104 cm2 V-1 s-1.
Two devices with size of 5×5-mm2 were prepared by using optical lithography. In the first, the active layers were segmented into four electrically insulated quadrants. Indium Ohmic contacts were realized on the corner of each quadrant (for readout) and on the back surface (for bias).
In the second, the QW was left unsegmented and covered by 400 nm of Al providing a single bias electrode, while four readout electrodes were fabricated on the back side by depositing and segmenting a Ni/Ge/Au layer. This configuration should be beneficial for the fabrication of pixelated detectors.
Photo-generated carriers can be collected at the readout electrodes by biasing form either the QW side or the back side of the devices during beam exposure. Individual currents obtained from each electrode allow to monitor both the position and the intensity of the impinging beam for photon energies ranging from visible to hard X-ray.
Such detector prototypes were tested with Synchrotron Radiation (SR), conventional X-rays and 400-nm laser light. The results obtained with X-ray SR show how these devices exhibit high charge collection efficiencies, which can be imputed to the charge-multiplication effect of the 2DEG inside the QW. Moreover, the position of the beam can be estimated with a precision of 800 nm in the segmented QW. A lower precision of 10 μm was recorded in the unsegmented QW due to the charge diffusion through the 500-μm-thick wafer. When tested with a 400-nm, 100-fs table-top laser, these devices responded with 100-ps rise-times to such ultra-fast laser pulses.

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Capacitive Division Image Readout - Modelling and simulation of new designs

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The Capacitive Division Image Readout (C-DIR) is a centroiding image readout for single photon counting detectors such as microchannel plate (MCP) photomultipliers and micro pattern gas detectors. Division of the event charge occurs through a capacitively coupled two-dimensional

matrix of electrodes to a small number of readout nodes where charge measurement followed by a position decoding algorithm is used to determine the event coordinate.
The capacitive nature of the C-DIR concept provides very high signal bandwidth for very fast timing applications and places a low capacitive load on the measurement electronics. In combination these qualities provide an enhanced image resolution/event timing performance envelope compared with traditional centroiding readout devices.
The C-DIR concept can be physically realised in a variety of electrode configurations and manufacturing methods. We describe various alternative C-DIR designs optimised for different detector formats performance requirements, and present simulations of performance augmented by experimental results from some of the designs.

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Muon Scattering Tomography Using Drift Chamber Technology

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Muon Scattering Tomography offers a powerful method to image the contents of cargo containers. Muons are highly penetrating, natural particles originating in Earth's upper atmosphere. At sea level muons have a flux of about 10 000 per square metre per minute. Most cosmic muons have sufficient energy to penetrate several metres of dense cargo, making them suitable for scanning cargo for shielded nuclear materials.
Muons scatter as they pass through materials via Coulomb Scattering. The degree of scattering is dependent on the density of the material. Nuclear materials have high densities and can be distinguished from normal cargo by measurement of muon scatter angles.
Two sets of muon detectors are positioned above and below the volume to be scanned. Each set takes a measurement of the trajectory of a muon as it passes through. AWE is currently researching the use of drift chamber technology for use in a detector system. A drift chamber contains gas which is ionised as a muon transverses the detector volume. Electrons are created in the ionisation and are accelerated to a central wire carrying a high voltage. As they drift towards the wire they gain enough energy to ionise further gas molecules. This creates an avalanche of electrons on the wire which is an amplification of the original signal. By timing this signal and measuring its strength it is possible to locate where the muon passed through. Then, by reconstructing the trajectories of the muon through the cargo and calculating its scatter angle it is possible, after a sufficient number of muons, to accurately determine the density and location of objects within the cargo container.
Muon technology is particularly powerful in the fact that nuclear materials shielded by lead stand out more than those without shielding due to the lead causing a high degree of scatter. The low-cost of the detector combined with its ability to construct a 3D image of any cargo in a short space of time (on the order of 1-2 minutes) makes it a very powerful tool for cargo screening purposes.

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Capacitive Division Image Readout - Rate and resolution measurements using adaptive pulse processing

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The Capacitive Division Image Readout (C-DIR) is a novel image readout offering major performance advantages over traditional techniques. C-DIR's very low electronic noise facilitates a combination of high spatial resolution and high event count rate capability. Coupling the C-DIR with microchannel plate photon counting and utilising a pulse digitisation approach allows the use of adaptive digital filtering to provide optimal, and dynamic, trade-off between count rate and image resolution. This technique enables a single instrument to accommodate scenes with large dynamic range whilst maintaining the ability for very high spatial resolution imaging when desired.
We present research results comparing various shaping schemes based on traditional analogue filter techniques that have been digitally implemented versus digital filters. Pulse processing using CR-RC, CR-RCn (semi-Gaussian), trapezoid and moving window deconvolution methods were tested revealing rate, resolution and adaptability performance.

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RadICAL - Directional Detector for Source Localisation

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A novel method for providing directionality for radiation detection is presented. The concept is based upon the fact that detector response depends upon two properties of the active component in the detector: the radiation pathlength and the area presented to a particle flux. Thus a rotating slab of detector gives a characteristic temporal response that can be used to identify the direction of the photon flux. We present ray tracing and Monte-Carlo modelling data that was used to evaluate the effectiveness of the system and design and build a prototype detector. This detector was then exposed to a variety of different sources to further evaluate the concept.

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Strategies for reducing the environmental impact of gaseous detector operation at the CERN-LHC experiments

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The emission of greenhouse gases is becoming an important subject for the design of future particle detectors and the operation of the present experiments. The particle physics detector community has already demonstrated to be sensitive to this topic at the design level: indeed, most of the gas systems recirculate the mixture injected. Contributions from R134a, CF4 and SF6 dominate the overall emission in terms of CO2 equivalent. Presently, gas mixture re-circulation and recuperation of gases from the exhaust mixture are the main strategies for reducing the environmental impact of particle detection activities. However, as long term prospective, also the use of less invasive gases should be investigated. The present contribution describes preliminary tests performed with a new recently developed Freon (R1234yf) and results obtained during operation of a large LHC detector system with recuperated CF4. The R1234yf has proposed as a replacement for R134a as a refrigerant in automobile air conditioners. In fact, R1234yf has a 100 year GWP (Global-Warming Potential) of 4, to be compared with 1430 being the 100 year GWP of R134a. Unfortunately, R1234yf is at the moment about 25 times more expensive than the currently used R134a. A small replica of a new gas mixer and recirculation system has been prepared for monitoring basic parameters like efficiency, pulse charge, streamer probability as well as long term performances of two Resistive Plate Chambers (RPC) detectors. Firstly, the new R1234yf

Freon was analysed with gas chromatographic and mass-spectrometer techniques. Subsequently, the gas system (mixer and recirculation) was tuned according to the new gas parameters. At the moment of writing, tests for the characterization of the detector performances and the evaluation of purifiers' performances are ongoing. A CF4 recuperation plant based on warm separation was developed in the past few years for a LHC-CSC (Cathode Strip Chamber) detector system using Ar-CO2-CF4 mixture. It is based on CO2 bulk separation through membrane, CO2 residual separation with 4 Å molecular sieve and final CF4 adsorption in 13X molecular sieve. The recuperation plant allows reducing the CF4 emission by more than a factor two. About 70 m3 have been recuperated during 2012 operation; however, the recuperated gas was never used since the risk of affecting the detector performances during data taking was considered too high. Now, the LHC-Long Shutdown 1 (where there is not data taking) offers the opportunity to test the effect of injecting the recuperated gas. Gas mixture composition and detector performances will be monitored all along the test with gas chromatograph, infrared analyser and dedicated detector monitoring.

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Performance Study of Electron Tracking Compton Camera with Compact System for Environmental gamma-ray Observations

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We have developed an Electron-Tracking Compton Camera (ETCC) that can determine the arrival directions of sub-MeV/MeV gamma rays for the use of environmental gamma-ray observations. It is a hybrid detector consisting of a gaseous TPC, which has a 10 cm square two-dimensional position sensitive micropixel gaseous detector for detecting a recoil electron track, and a positionsensitive scintillation camera, which is set at the bottom of the TPC, for the detection of the scattering gamma ray. We can reconstruct the arrival direction of every incident photon with an angular resolution of several degrees in FWHM, and select a perfect reconstructed compton event. Also, background charged particles such as a cosmic ray can be strongly rejected by using an energy loss rate (dE/dx) in the TPC. The detector has a large field of view (about 3 str). Because of these advantages, the ETCC is the detector suitable for the monitoring gamma-rays from radioactively contaminated soil. In particular, since an ETCC reconstructs all gamma rays including scattered background, we can measure the radiation intensity map over the FoV including energy spectrum. This feature enables us to estimate quantitatively a boundary condition for the necessity of decontamination. For the use of monitoring the environmental gamma-rays in the open, the compactness and portability is needed for the detector. In this conference, we will present the result of the performance study of the ETCC for the environmental gamma-ray observation.

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Characterising front-illuminated and back-illuminated e2v CCDs in the context of weak gravitational lensing

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The performance of two e2v CCDs which are beamline-irradiated to levels representative of a mission end of life are the subject of this study. A spot projection system was constructed in order to project pseudo-galaxies onto areas of the CCDs, each partially irradiated with end of life and half end of life proton fluences. The photon transfer behaviour of a front-illuminated CCD273 and back-illuminated CCD273 are compared alongside spot projection data which questions the integrity of CCD pixels in the presence of signal dependent charge-spreading. The effect of different device biasing and clocking schemes are also investigated, particularly in the contexts of linearity and charge transfer inefficiency mitigation. The research goal is to infer the deterioration of weak gravitational lensing measurement quality with respect to time and suggest optimum device operating parameters.

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Investigation of a possible physical mechanism for signal dependent charge sharing in CCDs

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Recent observations of significant nonlinearity in the observed noise statistics of Back Illuminated, deep depletion CCD sensors have been attributed to signal dependent charge sharing between pixels, after several more obvious explanatory possibilities have been eliminated. The sub-Poisson noise observed in these cases may be explained by a correlation between the amount of signal present in a pixel, and the likelihood of an arriving charge carrier to be diverted away from that pixel.
In this paper, we suggest and investigate a possible physical mechanism from which the observed correlation may arise. Using simplifying assumptions and analytical solutions of the potential and field distributions in the pixel, we show that differing potentials between neighbouring pixels (due to differing levels of collected charge) can lead to the effective sizes of pixels (as defined by the electric fields) changing. Using further simplifications, we present an approximate analytic expression for the effective pixel size which is dependent on pixel signal. Simple numerical simulations are presented which show that nonlinearity qualitatively similar to the observed results for CCD sensors can be produced by this model.
Finally, we obtain approximations for the probability distribution arising due to the model, from which mean and variance for given signal levels can be calculated. We show that the nonlinearity parameters extracted from these results are reasonably consistent with experiment.

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Characterization of Double Modified Internal Gate Pixel by 3D Simulation Study

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We have developed a novel photon detector concept based on Modified Internal Gate Field Effect Transistor (MIGFET) wherein a buried Modified Internal Gate (MIG) is implanted underneath the channel of a FET. In between the MIG and the channel of the FET there is depleted semiconductor material forming a potential barrier between charges in the channel and similar type signal charges located in the MIG. The signal charges in the MIG have a measurable effect on the conductance of the channel. In this paper a double MIGFET pixel is investigated comprising two MIGFETs.

By transferring the signal charges between the two MIGs Non-Destructive Correlated Double Sampling is enabled.
Electrical parameters of the double MIGFET pixel have been evaluated by 3D TCAD simulation study. Simulation results show the absence of interface generated dark noise, significantly reduced interface generated 1/f noise due to deep buried channel operation, well performing NDCDS readout, and blooming protection due to an inherent vertical anti-blooming structure. In addition, the backside illuminated thick fully depleted pixel design results in low crosstalk due to lack of diffusion and good quantum efficiency from visible to Near Infra-Red (NIR) light. These facts result in excellent signal-to-noise ratio and very low crosstalk enabling thus excellent image quality. The simulation demonstrates the charge to current conversion gain for source current read-out to be 0.89 nA/e.
Key words: device simulation, Back-Side Illuminated, BSI, image sensor, imaging, modified internal gate, MIG, ultra low noise, low dark-current, low crosstalk, high quantum efficiency, vertical anti-blooming, fully depleted, non-destructive readout, non-destructive correlated double sampling.

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Improvements to EMCCD technology through advanced semiconductor simulations.

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Electron Multiplying CCDs (EMCCDs) are a relatively recent class of devices that have found a variety of applications ranging from astronomy to microbiology. The key distinction from a conventional CCD lies in the addition of a multiplication register, which uses high electric fields to increase signal size through the process of impact ionisation. The result is a highly sensitive device, capable of single photon detection at high readout speeds. As such, EMCCDs have many applications where high sensitivity and high frame rate are a priority, including low light spectroscopy and LIDAR. Utilisation in future applications and adoption within a space environment hinges on further mitigation of undesirable device characteristics, including Clock Induced Charge (CIC) and the observed decrease in gain as a function of device age (the "ageing" process). Here we present a study aimed at further alleviating these issues through state-of-the-art simulations and laboratory measurements from sample devices.

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Empirical formula of a spatial resolution for a wavelength-shifting fibre detector coupled with a ZnS/6LiF scintillator for thermal neutron detection

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A spatial resolution of a wavelength-shifting (WLS) fibre detector coupled with a ZnS/6LiF scintillator screen was evaluated experimentally as a function of a scintillator thickness and a diametre of the WLS fibre. The spatial resolutions were measured separately with respect to the light spreading within the scintillator or within the layre of the WLS fibres. The empirical formula was derived that describes the two-dimensional spatial resolution of the detector.

The test detector head comprised of two, crossly-arranged WLS fibre arrays and a single ZnS/6LiF scintillator screen that was placed on top of the top WLS fibre array. A small fraction of the scintillation light generated in the scintillator in the n(6Li,alpha)t reaction escaped from the surface of the scintillator and they were re-absorbed in the top and/or bottom WLS fibre arrays while propagating through them. The measured spatial resolution was significantly related with the thickness of the scintillator and the diamtre of the WLS fibre, suggesting that the light spreading within the scintillator and the WLS fibre arrays dominated the spatial resolution of the detector.
The derived empirical formula would be useful to predict a spatial resolution of this type detector, particularly when designing and optimizing competitive detector performances such as a high spatial resolution and a high detector efficiency.

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Comparative Study of LaBr3(Ce) and CZT Array on Determination of Uranium Enrichment for Nuclear Safeguards Application

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Uranium enrichment is one of the most important factors in nuclear material safeguards. The accuracy of the IAEA's verification methods is dependent upon the type for a radiation detector used during inspections. The IAEA"s COMPUCEA (COMbined Procedure for Uranium Concentration and Enrichment Assay) employs the use of LaBr3 (Ce) to measure uranium enrichment at low-enriched uranium fuel fabrication plants. The most important feature of COMPUCEA is its use for on-site analytical measurerment. To improve accuracy and convenience of COMPUCEA as an in-field measurement instrument, this paper will examine ways of replacing LaBr3 (Ce) with cadmium zinc telluride (CZT). Low detection efficiency of CZT (which is the major drawback in radiation measurement) can be addressed by adopting several-CZT arrays. The Monte Carlo simulation (MCNPX) shows that a dual crystal array of two 1.5 cm x 1.5 cm x 0.75 cm has similar detection efficiency to that of a 5.08 cm (Dia.) x 2.54 cm (Length) LaBr3(Ce). Good energy resolution and the small size of the CZT would make it possible to develop more accurate and convenient COMPUCEA-like instrument. Adoption of an array-type CZT detector can also reduce power consumption. How to design an optimal CZT array, and to realize a CZT array-based uranium enrichment measurement system will be discussed in detail at the conference.

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Performance characteristics of the new detector array for the SANS2d instrument on the ISIS spallation neutron source

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The performance of the new position sensitive neutron detector arrays of the Small Angle Neutron Scattering (SANS) instrument SANS2d is described. The SANS2d instrument is one of the seven instruments currently available for users on the second target station (TS2) of the ISIS spallation neutron source. Since the instrument became operational in 2008 it has used two one metre square multi-wire proportional detectors (MWPC). However, these detectors suffer from a low count rate capability, are easily damaged, are expensive to repair and over the last two years have become increasingly unreliable. The new detector arrays consist of 120 individual position sensitive tubes filled with 15 bars of 3He. Each of the tubes is one metre long and has a diameter

of 8 mm giving a detector array with an overall area of one square metre. Two such arrays have been built and installed into the SANS2d vacuum tank where they are currently taking user data. Operation of the detector within a vacuum is essential in order to reduce air scattering. A novel, fully engineered approach has been utilised to ensure that the high voltage connections and preamps are located inside the SANS2d vacuum tank at atmospheric pressure, within air tubes and air boxes respectively. The signal processing electronics and data acquisition system are located remotely in a counting house outside of the blockhouse. This allows easy access for maintenance purposes, without the need to remove the detector from the vacuum tank. The design will be described in detail.
The initial measurements taken from a standard sample indicate that whilst the detector array itself only represents a moderate improvement in overall detection efficiency (~50% better) compared with the MWPCs, the count rate capability is increased by a factor of ~100 for a comparable position resolution (~8mm). A significant advantage of the new array is the ability to change a single tube in situ within approximately 1 day with a relatively small staff effort. The results obtained from the first user trials will be reported.

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Evaluation of two-dimensional multiwire neutron detector with individual line readout under pulsed neutron irradiation

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A multiwire-type two-dimensional neutron detector system using individual line readout and optical signal transmission method is developed for use in the Materials and Life Science Experimental Facility (MLF) at the Japan Proton Accelerator Research Complex (J=PARC). The sensitive area was 128 × 128 mm2 with a pitch of 1 mm in both directions (x and y), and the 256 signal lines are individually readout by signal-processing electronics. First irradiation experiments using pulsed neutrons are performed at the J-PARC/MLF. The developed detector could determine time-of-flight spectra and time-resolved two-dimensional images accurately with time range from 0 to 40 ms that arise from 25-Hz pulsed neutrons. The detector system exhibits a gamma-ray signals of 3.27 × 10-3 counts/pulse/(sensitive area), a deviation of position linearity less than 0.5%, and a spatial response of 1.8 mm full width at half-maximum. Finally, the validity of the detector system is confirmed by a neutron reflectometry using Ni/Ti multilayer.

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Microstructured silicon neutron detectors for security applications

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Neutron detection and the REWARD Project

Neutron detection is essential to intercept and find out the location of radiological threats like radioactive sources or special nuclear materials (SNM) that could be used to build improvised nuclear weapons or dirty bombs. To enhance nuclear security, the FP7 European project Real Time Wide Area Radiation Surveillance System (REWARD) has been developed. This project proposes a novel mobile system for wide-area radiation surveillance in real-time. The system is based on the integration of new miniaturized solid-state radiation sensors: a (Cd,Zn)Te detector for gamma radiation and a high efficiency neutron detector based on perforated neutron silicon detectors.

High efficiency silicon neutron detector

Neutrons do not interact in matter by ionization, so they are not easily detected by silicon detectors, whose working principle is based in the creation of electron-hole pairs. However, a silicon diode covered with a neutron-sensitive conversion layer can be used as an active neutron detector. If the reaction products, photons or charged particles, reach the silicon sensitive volume with enough energy and create a signal over the minimum threshold they will be detected. The REWARD project uses a novel 3D silicon detector as the base detector. The device is fabricated on a wafer with active thickness of 300 µm. High efficiency is achieved with sinusoidal or hexagonal channels (150 µm deep and 25 µm wide), etched in the silicon and filled with converter material, increasing the surface area of the converter in contact with the sensitive semiconductor volume. The converter material used in these sensors is powdered ^{6}LiF who has a cross section of 942 barns for the capture of thermal neutrons (0.025 eV) and give the following reaction:

$n +^6 LiF \rightarrow \alpha(2.05MeV) +^3 H(2.73MeV)$

The sensors were designed at IMB-CNM and fully fabricated at the Institute's clean room. Their active area is 1.0 cm^2 and the operating voltage is only 3 V.

Geant4 simulations

The Monte-Carlo code Geant4 v.9.6.1 was used to simulate both sinusoidal and hexagonal geometries with various ^{6}LiF densities. The simulations consists in a monoenergetic broad thermal (0.025 eV) neutron beam normally incident on the surface of the detector with a total of 10^6 neutrons per run. The statistical relative uncertainties were less than 0.1%. The simulations allow us to study the dependence of the neutron detection efficiency with the geometrical parameters.

Thermal neutron tests at IST/ITN

In order to study the response to neutrons of the detectors, it is necessary to test them with a neutron beam as monoenergetic and well-known as possible. The nuclear reactor of the Instituto Tecnológico e Nuclear in Lisbon was used for such aim. The intrinsic detection efficiency of the detectors for thermal neutrons and their gamma sensitivity as a function of the energy threshold were measured.

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The upgrade of the muon system of the CMS experiment

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The CMS muon system is based on three types of gaseous detectors, RPC, CSC and DT. While operating very well in the present conditions, upgrades are foreseen for each of the subsystems, necessary to cope with the increased pile-up, coming along with higher rates and radiation, during the upcoming periods of data taking.

Moreover, an important issue will be to make the system able to perform its delicate task of muon triggering and tracking also in the High Luminosity phase of LHC, foreseen to start after Long Shutdown 3 in 2023 and to last for about 10 years.

Studies devoted to asses the system perfomance stability for the future will be presented. In addition, the stategy - which is being developed - to complement the existing system with new detectors, based on GEM or improved RPC technologies, will be shown.

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A New Digital-Analog Multiplex Method Using Simple Adder Circuit

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Recently, In order to decrease dead space to increase efficiency, several research using monolithic crystal have been conducting in the field of PET scanner1. Since pixelation of photo detector is necessary to get exact gamma ray interaction location, read out channel will greatly increase. Signal multiplex plays a important role to decrease read out channels, but almost every pixel emits signal at the same time in the case of monolithic crystal, therefore separation of each channel has to be strongly required. Unlike conventional resistive division multiplex method1, we propose a new digital-analog multiplex method using a simple adder circuit to get not only channel information, but also energy information. Each output signal from a detector is digitized by comparators, this process is well known as Time-Over-Threshold method[3], and this digitized signals flow into an adder circuit. The relation between input resisters (Rin) and a feedback resister (Rf) contributes output voltage, which is the proportional to Rf/Rin. Therefore, by setting input resisters as the binary scale, added signal output can be separated by its pulse height, also pulse width has energy information. In order to validate the method, a 12mm x 12mm x 12mm GAGG[4] monolithic crystal was mounted on a 16ch HAMAMATSU MPPC. Each pixel of the MPPC is 3mm x 3mm. Comparator thresholds and bias supply were set at 100mV above baseline and 3.3V, respectively. The Input resisters of adder circuit were set at 1kohm, 2kohm, 4kohm, 8kohm, and so on, and the feedback resister was set at 500ohm. Output pulse from adder circuit was sampled by an Agilent Technologies L4534A digitizer, whose sampling rate and energy resolution are 20MSa/a and 16bit, respectively, and analyzed. So far, we had been tested 4ch multiplex. In this case, there are 15 patterns in multiplexed pulse height. By decoding it and counting pulse width, energy spectrums of Cs137 were clearly obtained in each channel. Since resolution of output pulse height of Each channel was about 7mV FWHM, we expected that at least 8ch multiplex can be possible. Now we have been extending to 8ch multiplex, additional results will be presented in the conference.
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Quality Control and Beam Test of GEM Detectors for Future Upgrades of the CMS Muon High Rate Region at the LHC

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Gas Electron Multipliers (GEM) are a proven position sensitive gas detector technology which nowadays is becoming more widely used in High Energy Physics. GEMs offer an excellent spatial resolution and a high particle rate capability, with a close to 100% detection efficiency. In view of the high luminosity phase of the CERN Large Hadron Collider, these aforementioned features make GEMs suitable candidates for the future upgrades of the Compact Muon Solenoid (CMS) detector. In particular, the CMS GEM Collaboration proposes to cover the high-eta region of the muon system with large-area triple-GEM detectors, which have the ability to provide robust and redundant tracking and triggering functions. In this contribution, after a general introduction and overview of the project, the construction of full-size trapezoidal triple-GEM prototypes will

be described in more detail. The procedures for the quality control of the GEM foils, including gain uniformity measurements with an x-ray source will be presented. In the past few years, several CMS triple-GEM prototype detectors were operated with test beams at the CERN SPS. The results of these test beam campaigns will be summarised.

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A Novel Pixellated Spectroscopic Detector Combined With a Broadband Monochromator to Produce Scatter-Free Images for the Improvement of Breast Cancer Detection

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This work aims to investigate an alternative approach to the use of an anti-scatter grid for removing scatter in breast cancer screening. The successful removal of scatter will aid in improving image quality in mammography and therefore improve the detection of features that suggest the presence of cancer. The work uses a novel pixellated spectroscopic detector combined with a broadband crystal monochromator. We present here results from the characterisation of the system and preliminary images. Compton-scattered X-rays that cause a reduced contrast on X-ray images have a lower energy than the primary beam. If the primary beam has a narrow energy band, the lower-energy scattered X-rays can be removed exploiting the spectroscopic capability of the detector, by simply windowing the detected spectrum around the range of the primary energy band. This essentially provides a scatter free image. The detector used for this work is a pixellated spectroscopic detector that consists of a 1mm-thick, 2x2cm2 CdTe crystal with a pixel pitch of 250 μm and an energy resolution of 0.8 keV at 59.9 keV. The monochromator used is a Highly Orientated Pyrolytic Graphite (HOPG) crystal that has a mosaic spread of $0.4°\pm0.1°$. This mosaic spread allows for a good photon flux for X-ray imaging with a conventional source. Characterisation of the monochromator was performed and initial data gave a bandwidth ranging from 2.8keV at 18keV to 5.6keV at 28keV. The initial imaging data demonstrated the magnitude of the scattered component and also the improvement in image quality brought by scatter removal. Existing work on the use of monochromatic radiation does not rely on scatter removal using spectrum windowing. This method has the benefit of reducing the delivered dose as virtually no primary radiation will be removed in the windowing process. Future work will involve extensive optimisation of the primary monochromatic energy for various breast thicknesses/densities. A method for analysing the contrast improvement due to the scatter removal will be developed and evaluated for each of the breast thicknesses/densities.

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A Novel gain stage for Microchannel Plate Imaging Photomultipliers

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Microchannel plate based photomultipliers are the major technology for single photon imaging at time resolutions below 200 ps. We describe a technique to improve microchannel plate (MCP) detector dynamic range and lifetime by means of a novel technology, an "active anode" employing atomic layer deposition (ALD) to provide an additional gain stage after the MCP. The technique has direct application to ring imaging Cherenkov (RICH) detectors for particle physics and other applications requiring time-resolved photon-counting imaging.
The ALD technique allows complex surfaces to be conformally coated with ultra thin films in a wide variety of materials. ALD has already been shown to benefit MCP detectors, allowing increased detector gain and reducing outgassing with dramatic benefit to detector lifetime.
We describe an additional gain stage behind the MCP stack comprising a mesh anode and reflection dynode and incorporating a two-dimensional image readout via the Image Charge technique. ALD is used to provide a dynode coating with high secondary electron emission and the resistive properties required for Image Charge. The additional gain stage allows MCP gain to be lowered increasing both the local and global count rate limits and enhancing detector lifetime. We present measurements of secondary electron emission from ALD coatings and imaging performance of an MCP detector employing the active anode device.

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Digital processing of signals from fast scintillation detectors

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Fast scintillation detectors such as LaBr3(Ce) and CeBr3 have appeared as a good candidate for timing and energy measurements in nuclear physics experiments and also for use in medical imaging modalities such as positron emission tomography (PET) systems. Since in such applications the number of data channels is generally large, a proper multi-channel data acquisition system is required to exploit the excellent properties of the detectors. In recent years, digital signal processing techniques have gained popularity for the development of multi-channel data acquisition systems due to their high degree of flexibility and stability and also the possibility of offline analysis. In this paper, we present the results of timing and energy measurements using digital signal processing of LaBr3(Ce) detectors. The photomultiplier (PMT) output signals from two identical LaBr3(Ce) detectors with a cylindrical shape (1.5" diameter and 2" tall) are directly digitized using an ultrafast digitizer with sampling rates adjustable up to 4 GSample/s and with 10-bits resolution. To extract energy information, the sampled signals were processed using different algorithms such as digital trapezoidal and integration-differentiation (CR-RC) pulse filters, as well as, with a simple integration of PMT current signals. The results show that the energy resolution does not critically depend on the type of pulse filter, and therefore, a simple integration of pulses is sufficient to produce an energy resolution comparable with the analog results (3.5% at 662 keV energy). The effect of pulse sampling rate on the energy resolution was also studied, indicating a degradation of the resolution with reducing the pulse sampling rate. In regard to the timing measurements, a digital version of constant-fraction discrimination (CFD) method was used. A time resolution of 240 ps (FWHM) was achieved using the energy lines of 60Co with a pulse sampling rate of 4 GS/s. This time resolution is superior to the result obtained with the standard NIM modules (305 ps) due to the possibility of a fine adjustment of the time pickoff parameters. However, our studies show that at lower sampling rates (below 1 GS/s), the digital timing can be limited by the aliasing error. By using an anti-aliasing filter before the pulse sampling process, a time resolution of 375 ps (FWHM) and an energy resolution of 3.5 % at 662 keV was achieved with a sampling rate of 500 MS/s. Pulses with such sampling rate can be conveniently processed with the available FPGA (Field programmable gate arrays) technology making it possible to build compact digital LaBr3(Ce) detection systems.

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Monte Carlo Simulations of Scintillation Detectors for Time-of-Flight X-ray Imaging

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Time-of-Flight x-ray imaging uses the Time-of-Flight of scattered photons to determine the point of scatter, providing three dimensional information about an object under inspection. The spatial resolution of the method is dependant upon the timing resolution of the detector. When applied to security cargo screening a large array of detectors is required, however large dimension detectors result in poor timing resolution. The present work describes Monte Carlo simulations, using GEANT4, of scintillation detectors of varying sizes for Time-of-Flight x-ray imaging, and the dependence of timing resolution on dimensions, photomultiplier tube (PMT) characteristics, scintillation material, and reflector material. Simulations indicate that timing resolution is strongly dependant upon the number of reflections that occur inside of the crystal and the PMT should be well matched with the scintillator dimensions. A timing resolution of less 700 ps (FWHM) is possible using either a 3" or 2" diameter plastic scintillator, when exposed to x ray photons that have undergone a large angle Compton scatter. Experimental coincidence measurements are compared with simulation results to determine the validity of the simulations.

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(Invited) Energy dependence of detectors for 3D dosimetry of light ion beams

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Mapping and verifying 3D dose distributions form an essential procedure in the adequate treatment process of cancers with radiotherapy. The main requirements for 3D dosimeters are a spatial resolution sufficient for resolving the dose variations of interest, efficient readout and a response proportional to dose. Common methods to obtain 3D dose distributions include, scanning systems with point detectors such as ionisation chambers or diodes, linear or 2D arrays composed of ionisation chambers or diodes, 2D films and 3D-distributed radiosensitive agents in gels or plastics. Point detectors are usually not efficient for 3D dosimetry but have some applications, e.g. if the volume to be scanned is limited or if it is sufficient to obtain dose profiles along three axes only. Linear arrays are efficient to obtain 2D dose maps but can still require long acquisition times for full 3D dose distributions. 2D arrays, on the other hand, are efficient but have often the disadvantage that resolution is limited given limitations on the amount of signals that can be read-out. Distributed radiosensitive agents in films, scintillating plates, gels or plastics provide a high resolution but the former two require laborious readout procedures while the latter two require optical or magnetic resonance interrogation with tomographic reconstruction. For scanned ion beams, an additional constraint is that dose scanning methods are not an option in terms of efficiency since for every dose point the entire scan sequence has to be delivered. 2D arrays or 3D dosimetry methods are often the only practical option. A particular requirement of scanned ion beams is the measurement and verification of spot positions. Deformation of the profile due to inhomogeneities of the 2D detectors used can result in an erroneous determination of the centre of the spot.
For light ion beams, a specific issue encountered is that the radiosensitivity of many physical or chemical detectors is dependent on the energy of the charged particle passing the detector volume. It is thus essential that this energy dependence is well-understood and corrected for. One of the

contributing factors is the difference in energy absorption between the detector material and the phantom material (water or tissue) but in most cases the energy dependence is predominantly related to the ionisation density which, for a given type of projectile, increases with decreasing particle energy. In solid state detectors that are based on the creation of electron-hole pairs, such as silicon diodes, mosfets, diamonds and luminescence detectors, an increased ionisation density modifies the probability of recombination and consequently also the dose response. Other processes involving the mobility of electron-hole pairs may also be affected by ionisation density. In chemical dosimeters such as Fricke gels, polymer gels and radiochromic films or plastics, the increased ionisation density changes the yield of primary species diffusing out of the ion tracks resulting in a modified dose-sensitivity and for many of those, also the probability of termination reactions increases with increasing ionisation density resulting in a loss of signal. Even for detectors that are generally considered to exhibit little energy dependence such as ionisation chambers and calorimeters, the effect may not be negligible for ion beams. For ionisation chambers, the mean energy required to produce an ion pair is energy dependent resulting in a small quenching of 1-2% of the Bragg peak, while for calorimeters, the primary instruments for the unit of absorbed dose, the physicochemical heat defects due to the formation of lattice defects or chemical reactions are energy dependent for ion beams.
An overview of 3D dosimetry technologies for scattered and scanned ion beams will be presented and signal quenching mechanisms and sources of response non-uniformities will be discussed. In conclusion, energy dependence of any 3D dosimeter should be considered and corrected for as well as any non-uniformity in the detector's dose response.

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PGRIS: Towards portable Compton camera imaging

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The PorGamRays project has developed a portable gamma-ray spectrometer with imaging capabilities. This detector has applications within the medical, security and nuclear decommissioning fields. The current PorGamRays detector utilises the Compton camera principle with two CZT crystals and adapted ASIC readouts. The next phase of the project, PGRIS, will utilise newly developed ASICS that will increase energy range which can be imaged. These ASICs will be implemented along with new CZT detector modules. Real-time Compton imaging capability is also under development. This presentation will summarise the results of testing and characterisation of this Compton camera setup as well as the development of real time imaging with the portable Compton camera system.

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Dual-energy mammography with a pixellated spectroscopic detector

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Dual energy X-ray techniques allow an object to be decoupled into two components – typically, soft tissue and bone, or soft tissue and a contrast agent 1. Such techniques normally rely on the acquisition of two images, requiring increased dose to the patient, and potentially carrying the risk of incorrect image registration due to patient motion. This limitation is removed by using a spectroscopic, position-sensitive detector, which allows the two images to be obtained by integrating, pixel by pixel, appropriate bands of the spectrum transmitted from a conventional, polychromatic beam.
The HEXITEC collaboration 2 has developed a pixellated spectroscopic system based on CdTe detectors and dedicated read out electronics.
This paper will present results from dual-energy imaging for contrast agent mammography using custom-designed phantoms, commercial iodinated contrast agent agent (Niopam © 150, Bracco) and a HEXITEC system comprising a 1-mm thick, 20x20 mm2 CdTe sensor with 250 μm pixel pitch. The dual-energy algorithm proved to perform consistently better, in terms of detail visibility, than a simpler K-edge subtraction algorithm, having less stringent requirements in terms of position and width of the spectral bands to be integrated. Results from the comparison between the two algorithms will be presented, as well as comparison with conventional dual-energy imaging. Moreover, the dual energy algorithm was used for calculating the concentration of contrast agent in tubes of different diameter; the calculated concentration proved compatible with the actual one for a range of concentrations and of tube sizes.

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ProSPECTus: A Compton Camera For Medical Imaging

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Medical imaging is an expanding field tasked with improving diagnostic capabilities. The ProSPECTus project is a Single Photon Emission Computed Tomography (SPECT) system that employs highly segmented semiconductor detectors in Compton camera mode. The ProSPECTus system has been designed to alleviate the limitations present in current SPECT systems.
The basic principle of Compton imaging is that a gamma ray interacts at least once with each detector and deposits its full energy. The energy deposits and position of interaction in each detector is then used via the Compton Scatter formula to locate the position of the incoming radiation.
The ProSPECTus system consists of two highly segmented position and energy sensitive detectors. Both detectors are housed in a single custom-made cryostat. The first detector is made of Lithium drifted Silicon with active area dimension of (64 x64x 9) mm and 256 voxels of size (4 x4 x 9) mm, The second is made of high purity Germanium with active area dimensions (60 x 60 x 20) mm and 141 voxels of size (5 x5 x 20) mm.
A prototype ProSPECTUs system has been set up and optimized to acquire Compton imaging data with point sources and custom made medical phantoms, in order to show and quantify the performance capabilities of ProSPECTus in terms of image resolution and efficiency.
Simulations have been run using GAMOS (Geant-4 based Architecture for Medicine Oriented Simulations) to investigate the influence of position resolution on image quality. It has been found a position resolution of 1mm3 is needed for an optimum image. Pulse shape analysis algorithms and databases are being adapted and developed to improve the position resolution of the ProSPECTus detectors beyond voxel sizes.

Presented will be the basic concepts of Compton imaging, simulation and reconstructed image results of the position resolution investigations carried out, as well as the experimental images acquired with point, extended and phantom sources.

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(Invited) Direct-detection Monolithic Active CMOS sensors for X-ray Free-Electron Lasers and future ultimate storage ring light sources

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X-ray Free-Electron Lasers (XFELs) are now bringing new opportunity in coherent X-ray Science. Future X-ray sources such as high-repetition XFELs and ultimate storage ring (USR) light sources are anticipated to advance CXS further by delivering higher repetition rate and higher brilliance of coherent X-ray beam. In this talk, we first review the current detector status at the XFEL facility SACLA 1, and try to outlook the future opportunities from the viewpoint of X-ray imaging detectors by discussing the lessons learned in the development of SOI sensor technologies 1. Finally, a proposal of a staked-sensor concept for future photon science in the photon energy range up to 30 keV will be presented.
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Optimization of charge collection and radiation hardness of edgeless silicon pixel sensors for photon science and HEP applications

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Recent progress in active-edge technology of silicon sensors enables the development of large area tiled silicon detectors with small dead space between modules by utilizing edgeless sensors. Such technology has been proven in successful productions of ATLAS and Medipix-based silicon pixel sensors by a few foundries. However, the drawbacks of edgeless sensors are non-uniform charge collection by edge pixels and poor radiation hardness for ionizing radiation. In this work, the charges, produced by X-rays and other ionizing particles, collected by edge pixels of edgeless sensors with different thicknesses and polarities, have been calculated using a developed model. The model takes into account the electric field distribution inside pixel sensor, the absorption of X-rays or other ionizing particles, drift and diffusion of electrons and holes, charge sharing, and threshold settings in ASICs. It is found that the non-uniform charge collection by edge pixels is caused by the strong bending of electric field and the non-uniformity depends on bias voltage, sensor thickness and distance from active edge to the last pixel (also called "edge space" for short). In addition, the last few pixels close to the active edge of the sensor with a commercial design are not sensitive to low-energy X-rays and other ionizing particles for sensors with thicker Si and smaller edge space. The results from model calculation have been compared to measurements and good agreement was obtained, which gives us confidence that the model can be used to optimize the edge design. From the edge optimization, it is found that in order to guarantee the sensitivity of the last few pixels to low-energy X-rays and other ionizing particles, the edge space should be kept at least 50% of the sensor thickness.

In addition, the radiation hardness of edgeless sensors with different polarities, i.e. p^+n, n^+p and n^+n with p-spray or p-stop, has been investigated using SYNOPSYS TCAD with radiation damage parameters implemented, especially for surface damage produced by ionizing radiation with extremely high doses. Results show that if no conventional guard ring is present, none of the commercial designs are able to achieve a high breakdown voltage (typically < 30 V) after irradiation to a dose of ˜10 MGy. Finally, a radiation-hard pixel and edge design for edgeless sensors will be discussed according to the optimization results from TCAD.

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Charge Collection Efficiency of micro-strip Silicon Sensors Designed for studying charge multiplication after hadron irradiation

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The signal induced by minimum ionising particles in silicon strip detectors specially designed to investigate the process of charge multiplication has been studied by research groups within the CERN RD50 collaboration. In particular, various geometries of the implanted strips have been implemented on miniature (˜1x1 cm^2) micro-strip sensors on a 6” wafer to observe the effect of these variations on the electric field strength. The sensors, produced by Micron Semiconductor Ltd, vary in strip pitch and strip width, in the use of intermediate biased or floating strips between the readout strips and also in sensor thickness. In addition to the standard implant process, the implant energy for the phosphorous doping (n-type strips) and the diffusion time were increased for some devices to study the possible impact of the depth junction profile on charge multiplication. Charge collection measurements were performed with the ALiBaVa readout setup before and after irradiation with a proton fluence of 1e15 neq/cm^2 and neutron fluences of 1e15 and 5e15 1MeV neq/cm^2 (neq/cm^2). Several sensors exhibit enhancement of the collected charge compared to the standard sensor (pitch 80µm, width 25µm) after neutron irradiation of 5e15 neq/cm^2. Results of ongoing room temperature annealing studies, as well as TCT/eTCT (Transient Current Technique / edge TCT) studies will be presented.

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Studying defects in the silicon lattice using CCDs

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Silicon has long been the material of choice for the production of detectors for many applications, from space astronomy to synchrotron research. When operating in space, or within a synchrotron

or other accelerator, the detector can be subjected to a harsh radiation environment. The presence of these high energy electrons, protons and gamma-rays can lead to radiation-induced damage within the silicon lattice of the detector, creating further defects or "traps" in addition to any defects intrinsic to the lattice.
Charge-Coupled Devices (CCDs) have been used for many years to populate the focal planes of space telescopes, with recent examples ranging from the Hubble Space Telescope to the more recently launched ESA Gaia mission. The radiation environment in such missions is often dominated by high-energy protons, and leads to traps which act to capture electrons from signal charge packets as they are transferred through the device Any captured electrons are then released later in time, with this time determined by the emission time constant of the trap species in question. The repeated capture and release of signal as it is transferred through the CCD produces a "smearing" effect, resulting in a change in shape of the objects imaged. This change in shape is not only undesirable, but has particular importance to future applications such as the ESA Euclid mission, in which the subtle shape changes due to weak gravitational lensing are to be measured.
In order to correct against any radiation damage present in a CCD, one must be able to produce a model that accurately represents the transfer of charge through a device containing such traps. While current models are often based on fitting to observed data, it is now highly desirable to be able to actively predict the effects of any radiation on the device through a deeper understanding of the defects present in the lattice, at a sub-pixel, single-trap level. However, currently our understanding of defects within silicon has been based largely on techniques which analyse the average properties of many traps, often over several trap species.
Here we present a selection of methods, both experimental and simulated, that can be used to begin to study populations of lattice defects down to individual defects themselves. These studies have enabled the investigation of not only the defect densities and the device-averaged trap parameters, but also the properties of individual lattice defects in the device, en route to actively predicting the impact of the radiation environment before launch.

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Thin n-in-p planar pixel sensors and active edge sensors for the ATLAS upgrade at HL-LHC

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Silicon pixel modules employing n-in-p planar sensors with an active thickness of 200 µm, produced at CiS, and 100-200 µm thin active/slim edge sensor devices, produced at VTT in Finland have been interconnected to ATLAS FE-I3 and FE-I4 read-out chips. The thin sensors are designed for high energy physics collider experiments to ensure radiation hardness at high fluences. Moreover, the active edge technology of the VTT production maximizes the sensitive region of the assembly allowing for a reduced overlapping of the modules in the pixel layer closer to the beam pipe. The CiS production includes also four chip sensors that approach the module geometry planned for the outer layers of the ATLAS pixel detector upgrade to be operated at the HL-LHC. The modules have been characterized using radioactive sources in the laboratory and with high precision measurements at beam tests to investigate the hit efficiency and charge collection properties at different bias voltages and particle incidence angles.
The performance of the different sensor thicknesses and edge designs are compared before and after irradiation up to a fluence of 1.4×10^16 n_eq/cm^2.

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The TORCH PMT:A close packing, multi-anode, long life MCP-PMT for Cherenkov applications

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Photek (UK) and the TORCH collaboration are undertaking a three year development program to produce a novel square MCP-PMT for single photon detection. The TORCH detector aims to provide particle identification in the 2-10 GeV/c momentum range, using a Time-of-Flight method based on Cherenkov light, and has been proposed for the LHCb Upgrade. The MCP will provide a timing accuracy of ˜40 ps, and its development will include the following properties: 1. Long lifetime up to at least 5 C / cm2 of accumulated anode charge without degradation in sensitivity. Previous work published by Photek has demonstrated a significant lifetime improvement in an MCP-PMT when the MCP is coated by Atomic layer Deposition (ALD). 2. Multi-anode output with a spatial resolution of 0.4 mm and 6 mm respectively in the x and y directions, incorporating a novel charge-sharing technique. 3. Close packing on two opposing sides with an active area fill factor of 88% in the x direction. First results will be presented of the charge-sharing anode. The building and testing of long lifetime prototypes and high fill factor (square) tube body shape developments will be also described. The front-end read-out of choice is currently the NINO ASIC. The method of coupling the MCP-PMT output pads to a PCB through an ACF film will be described. This minimises any parasitic input capacitance by allowing very close proximity between the NINO and the detector. The gain and performance uniformity of the PMTs will be compared with current industry standards. We will also report on software simulations that factor in the pulse height variation from the detector, NINO threshold levels and potential charge sharing techniques that enhance the position resolution beyond the physical pitch of the pixel layout.

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The kaon identification system in the NA62 experiment at CERN SPS

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The main goal of the NA62 experiment at the CERN SPS accelerator is to measure the branching ratio of the ultra-rare $K^+ \to \pi^+\nu\bar{\nu}$ decay with 10% accuracy. This will be achieved by detecting $\sim$ 100 $K^+ \to \pi^+\nu\bar{\nu}$ decays with a ratio signal/background $\sim$ 10 in 2-3 years of data taking starting in October 2014. NA62 will use a high-energy unseparated charged beam, with kaons corresponding to $\sim$ 6% of the beam, and a kaon decay-in-flight technique. Since pions and protons cannot be separated efficiently from kaons at the beam level, the identification of kaons within a 750MHz particle rate is mandatory. The time information is also essential to reconstruct the $K^+ \to \pi^+\nu\bar{\nu}$ decay and to guarantee the rejection of background induced by accidental overlap of events in the detector. A differential Cherenkov detector (CEDAR) filled with Hydrogen or Nitrogen gas, and placed in the incoming beam, will perform the fast identification of kaons, before their decays, with an efficiency of at least 95%. The CEDAR is insensitive to pions and protons and will provide precise time information with a resolution of at least 100ps. With respect to previous applications, the CEDAR will work within NA62 under unprecedented beam conditions. To stand the particle rate and to meet the performances required, an upgraded version (CEDAR-KTAG) with new photon detectors, readout, mechanics, cooling and safety systems

has been proposed and realised for NA62. The CEDAR-KTAG upgrade has been successfully commissioned during a physics run at CERN in 2012. With half-detector equipped, the measured time resolutions are already within the required detector performances and the capability to distinguish between kaons and pions is validated by pressure scan results.